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The Implementation Of Innovative And Sustainable Construction Materials

Grist, Ellen

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The Implementation of Innovative and Sustainable Construction Materials

Ellen Grist

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Abstract

This research uses a novel construction material (lime-pozzolan concrete) and real-world project (a school) as a vehicle for investigating the *implementation* or *applied-innovation* process in construction. The implementation of new technologies at a product-level is recognised to be an antecedent of technological change in the construction industry.

A ‘real world’ construction project aiming to *implement* a novel lime-pozzolan concrete in the field, has been used as a process-tracing case study. Rigorous analysis of this case study project, expressly focusing on project-level communication, has shown the implementation of innovative and sustainable materials to be a complex, socio-technical process. With the aim of identifying opportunities to improve project-level design processes in order to support the uptake of innovation and sustainable solutions, twelve high-level theories have been built on twenty-five emergent themes. Collectively these insights demonstrate that implementation processes, once initiated, are experiential, social, contextual, active, interactive, temporal, intentional and mutually constituted phenomena.

On the strength of empirical findings this thesis argues for a radical shift in managerial attention from the outcome of the process to the process itself; specifically focused on the experience of the design team as process participants.

Laboratory testing and initial field trials have demonstrated the technical feasibility of producing structural grade lime-pozzolan concretes with 28-day compressive strengths of up to 50MPa. The lime-pozzolan concretes were ternary combinations of hydraulic lime (NHL5), ground granulated blastfurnace slag (GGBS) and silica fume (SF).

The use of NHL5 in conjunction with pozzolanic materials has been shown to be a viable ‘low-carbon’ alternative to CEMI or CEMIII/A in certain circumstances, although this work has demonstrated that the potential savings in the embodied CO_2 and energy of lime-pozzolan concretes are highly dependent on the boundaries of the analysis. Moreover the potential for lime-pozzolan concrete with a lower still CO_2 and energy intensity than any concretes tested to date has been identified.

Overview of the portfolio

Introduction

PART A: Exploration

Explore: *'to investigate, to find out, to search for, to try, to examine, to scrutinize, to probe'*
Oxford English Dictionary

Part A of this thesis covers the testing and development of a novel, low-CO_2 concrete based on hydraulic-lime and modern pozzolanic additions.

PART B: Implementation

Implement: *'to complete, to perform, to carry into effect; to fulfil; to carry out, to execute'*
Oxford English Dictionary

Part B of this thesis is a case study focusing on the attempted implementation of this novel, low-CO_2 concrete in a 'real world' construction project.

Overall conclusions

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Preface

This research programme looks at the sustainable construction materials not from an ethical perspective but from a phenomenological perspective. An ethical research approach demands starting with a fixed definition of 'sustainability', so as to be able to argue what is and what isn't, and what is more or less 'sustainable'. Typically, whether or not a development *'meets the needs of the present without compromising the ability of future generations to meet their own needs'* (World Commission on Environment and Development, 1987) - the Bruntland Commission's well-known definition of Sustainable Development, now so over used as to render it almost meaningless. Faced with the complexity of evaluating the social, economic and environmental dimensions of 'intergenerational equity', sustainability in the built environment is more often than not reduced to environmental impact, or further still to embodied CO_2 and energy. Even this simplification, arguably a dubious basis for ethical decision-making, is far from clear-cut in practice as this research has shown.

Rather, this phenomenological approach to sustainability starts with the premise that the current trajectory of human development is inherently 'unsustainable'. This thesis builds from the assumption that technological change is essential and proceeds on the understanding that sustainability demands our ability to cope with and manage technological change.

Rohracher (2003) purports that technological change is predicated on human choice. This thesis goes one step further in arguing that choice alone is not sufficient to bring about change, because change demands action (mobilised-choice). Rather, it is argued that technological change is predicated on human behaviour, which is more, or less, a product of human choice. In the dialogue about the transition to new technologies, the emphasis on 'implementation' puts human action right at the centre of the sustainability story. Specifically, this thesis focuses on managing the transition to a more sustainable construction of the built environment from a socio-technical perspective.

Ramboll prides itself on its commitment to innovation and over the years has celebrated numerous awards for delivering highly innovative projects. The nature of the construction industry is such that every project provides an original context for any technology or system. This offers a wealth of opportunities for creative designers to imagine and implement pioneering solutions that change the landscape of possibilities. For Ramboll the capability to manage technological change at a project-scale is essential for sustaining and extending their reputation and competiveness. A more holistic understanding of the implementation process is expected to increase their ability to deliver pioneering solutions, opening up future technological possibilities and enhancing their reputation (Chun, 2006).

In the light of the discrepancy between the ‘designed’ and ‘actual’ performance of ‘green’ buildings there is a growing emphasis on human behaviour in the design and delivery of the built environment (Gill et al., 2010). Whereas post-occupancy studies focus on the behaviour of building users this study focuses on the behaviour of building designers. Studies at either end of the deign process, are revealing the complexities of purposive and irrational human-social behaviour and highlighting the subtleties of sustainable design.

The methodological approach was to follow the story of an innovative and sustainable construction material in the ‘real-world’. Structural lime-pozzolan concrete was selected as the case study construction material, in this research programme. Although a substantial amount of material testing and development in the laboratory was conducted as part of this research programme, lime-pozzolan concrete itself was not the unit of analysis. Rather, the unit of analysis was the socio-technical system that comprised both the novel technology and the ‘relevant social group’, which were observed to be ‘mutually constituted’ (Harty, 2010).

1 Thesis Introduction

This thesis considers the ***implementation of innovative and sustainable construction materials*** in the construction industry.

1.1 Implementation

As a corollary of ancient Greek rhetoric, valuing intellectual thought (*theoria*) over practical work (*praxis*), pure research has long enjoyed superiority over applied research (Godin, 2006). Yet, socioeconomic progress is, and always has been, contingent upon the application of pure science. It is this 'application', this 'implementation', that is the focus of this research project.

Implementation in this project is defined as *the process by which science translates into socioeconomic progress*, or in short *applied-innovation.* This definition is a slight variation on the definition of 'applied-innovation' proposed by Godin (2006), purposefully removing the 'mechanism' metaphor. Implementation is recognised to be a core discipline of engineering, which is defined 'the action of working artfully to bring something about' (Oxford English Dictionary, 2013).

Specifically, this project looks at the implementation of novel and sustainable material technologies in the context of the built environment. To preserve attention on the profoundly purposeful activity that is implementation or applied-innovation, definitions of 'novel' and 'sustainable' materials are expressly considered later in this thesis.

1.2 Implementation in practice

Across the globe individuals and organizations are imagining and developing new or improved technologies that will reduce the damaging impact of human society on the planet; new renewable energy technologies, new low carbon materials, new optimized processes and systems. However, the current disjointed scenario of academic research grants, corporate Research and Development (R&D) programmes and small-scale knowledge transfer initiatives, is not currently realising, nor is it going to realise, the full benefit of these new technologies; at least not in the short time scales for measurable impact imposed by government targets, such as carbon emission reduction targets. The biggest challenge facing the built environment is not designing more sustainable solutions and technologies but actually implementing them. As Govindarajan and Trimble (2010) stress 'there is too much emphasis on ideas, not nearly enough emphasis on execution'. Recent research, looking at sustainable practices in the construction industry, substantiates this problem; ‘In discerning whether firms were applying sustainability practices to projects, the gap between intention and implementation was clear’ (International Council for Research and Innovation in Building and Construction, 2009).

1.3 Innovation in construction

Schumpeter (1934) in his influential work ‘The Theory of Economic Development’ emphasised that innovation is crucial for economic development. Innovation is also a central tenet of sustainable development; simultaneously creating jobs whilst providing an opportunity to develop cleaner technologies that reduce our impact on the natural environment (Dewick and Miozzo, 2002).

In the construction industry, innovation is heralded as a means of improving growth and competitiveness (Morrell, 2011), but the significance and challenge of implementation, as an essential part of the innovation process, is rarely emphasised. Yet, only through implementation can any innovative solution deliver the benefits it anticipates. To capitalise on the investment made in research activities and to deliver the benefits associated with cleaner, lighter, more efficient technologies; the global industry urgently needs to identify mechanisms for closing the loop between ideas and reality. This thesis addresses the *implementation* of new technologies, which it argues is the greatest global challenge for a sustainable built environment. Implementation is considered to be what Govindarajan and Trimble (2010) express as ‘the long hard journey - from imagination to impact’ and what the Technology Strategy Board (TSB) describe as ‘from concept to commercialisation’ (Technology Strategy Board, 2011).

It is argued that ‘engineers are born to innovate’ (Whitelaw, 2011) yet the construction industry has received on-going criticism for its lack of innovation (Nam, 1989, Miozzo, 2004, Reichstein et al., 2005, Drejer and Vinding, 2006) and numerous authors have expounded the specific challenges of innovating in the context of the built environment (Blayse and Manley, 2004, Dewick and Miozzo, 2004). That the characteristics of the end product ‘immobility, complexity, uniqueness, durability, costliness and high risk of failure’ (Nam and Tatum, 1988, Gann, 1994) are inherent in construction output and are thus unavoidable. Furthermore, globalized markets and increased computer processing are only increasing the size, complexity and capital costs of construction projects. Equally, the ‘fragmented, conservative, mature and highly regulated’ characteristics of the industry itself, and its ‘low profit margins', have proved difficult to leverage, despite industry reports and multiple calls for procurement reform (Latham, 1994, Egan, 1998, Morrell, 2011). Though well documented these issues seem so vast and intractable, they tend to disempower those individuals who make design decisions and act to reinforce a hopeless inevitability.

Kline and Rosenberg (1986) claim that, 'the systems that make up the innovation process are among the most complex known (both technically and socially).' Technical and economic considerations account only partially for the complexity of innovation systems. Considering the implementation of new sustainable materials in construction; a technical analysis would highlight the challenges of proving the long-term behaviour of immature technologies and understanding their interaction with other physical systems. An economic analysis would emphasise the challenges of competing in established and regulated financial markets. Innovation, and more specifically implementation, spans the boundaries of both technology and economics; but neither discipline, nor an understanding of both, can wholly describe or predict the success or failure of efforts to adopt novel solutions in construction. Dubois and Gadde (2002) have undertaken a systematic analysis of the construction industry, which they describe as a 'loosely coupled system'. Given the boundary-spanning nature of innovation, a systems perspective is argued to be the only approach offering a holistic enough view to explore this complexity.

On the challenge of innovation Akrich et al. (2002) purport that, 'we must not believe for a moment those edifying stories which retrospectively invoke the absence of demand, technical difficulties or inhibitory costs.' Technical and economic challenges, to the implementation of sustainable solutions in construction, cannot be ignored; but nor is it helpful to presuppose that these factors dictate or dominate project outcomes. Rohracher (2001) goes as far as to say, 'the challenge of green building is only to a minor extent the search for enhanced technical systems'. What is much more challenging is the social embedding and socially interactive process of designing, constructing and using buildings'. This thesis approaches the challenge of implementation from a soft systems perspective, reflecting on some of the psychological, social and political aspects of applied-innovation as a human and socially-interactive process; both at an individual and organizational level. That is it recognizes that innovation is a value-laden process, shaped by the interests, beliefs and actions of a collection of idiosyncratic human actors.

One of the principal challenges of implementation in construction is that innovations are not adopted within organizations, but in the context of one off projects (Dewick and Miozzo, 2002). Unlike an individual purchase decision, materials are selected and specified by a design team, often on behalf of a client. Although the unique nature of construction projects, does contribute to the socio-technical complexity of innovation in construction, it does also provide recurring opportunities for individual decision makers, design teams and construction organizations to evaluate and improve the project-level design process.

Critically, this thesis argues that social processes can be designed and managed to gain leverage within complex systems. Govindarajan and Trimble (2010) state that, 'The limits of innovation in large organizations have nothing to do with creativity and nothing to do with technology. They have everything to do with management capability', going on to say, 'what they {large organisations} lack are the managerial skills to convert ideas to impact.'

Personal and organizational challenges to implementation of new and sustainable technologies and services are widely acknowledged in literature (Harty, 2008), but typically as conclusions. Given that there is a desire for innovation in construction (Atkin, 1999, Seaden and Manseau, 2001, Eaton et al., 2006, Morrell, 2011) this thesis takes these reported conclusions as leads for identifying points of intervention in the socially-interactive dimension of the overall system.

1.4 Structure of the thesis

It has been said that there are two types of innovation: *exploratory* and *exploitative* (Li et al., 2008), concepts that were outlined in a seminal paper by March (1991), in the context of organizational learning. Exploration was argued to 'broaden an organization's capabilities' and exploitation 'to deepen them'. Acknowledging a necessary trade-off between these two activities, March (1991) warned organizations' of the dangers of neglecting either. What March's model did not convey was the importance of linking exploration and exploitation together. In this thesis *Implementation* is argued to be the value-realizing, technology-translating, socially-transforming step between exploration and exploitation. This extension of March's (1991) model is the basis of the structure of this thesis, which is divided into two main sections: Part A: Exploration and Part B: Implementation.

Exploration, Part A of this thesis, covers the testing and development of a novel, low-CO_2 concrete based on hydraulic-lime and modern pozzolanic additions.

Implementation, Part B of this thesis, is a case study focusing on the attempted implementation of this novel, low-CO_2 concrete in a 'real world' construction project.

1.5 Aims and Objectives

The overarching aim of this research was to gain a deeper understanding of the social choices, and actions that they mobilise, in the pursuit of technological change (Rohracher, 2003), in order to improve the management of applied-innovation processes in construction.

This industry-based research programme was part sponsored by Ramboll, a multidisciplinary engineering and design consultancy, whose primary objective was to build their innovative capacity and enhance their reputation for the delivery of innovative solutions. The focus on sustainable construction materials reflects Rambolls desire to deliver not only innovative, but increasingly responsible engineering solutions.

The results of the research were expected to increase the innovative capacity of Ramboll as a company by educating and equipping project managers and engineers to support innovation at a project level.

With the aim of enhancing innovative capacity at a project-level, the objective of the research was to build generalizable theories about the nature of applied-innovation processes in construction grounded in empirical reality. Specifically in this study, the implementation process has been considered through the lens of a single innovative technology – lime-pozzolan concrete. Through this lens, the research aimed to reveal a deeper and more holistic understanding of the status quo. Generalizable insights into current practice were recognised to be valuable in evaluating and designing new ways of working going forward.

Generalizable theories about project-level innovation processes in construction are expected to be of broader interest to construction professionals, who in the face of growing concern about the environment is being expected to deliver, if not to lead, transformative change in the expansion and preservation of the built environment.

2 Overall research approach

2.1 Process view

This research uses a novel product (lime-pozzolan concrete) as a vehicle for investigating the applied-innovation *process* in construction. The emphasis on process in this research adopts a Hegelian ontology, presupposing that reality is not a static but dynamic, experienced in the 'flux of existence'. Notions of change, development and progress can only be comprehended in the light of Hegel's philosophy of 'becoming' (Redding, 2013). Commenting on the need to mainstream green building design, Reed and Gordon (2000) acknowledge 'What hasn't been done are "process case studies"'. This study is just that.

2.2 Systems view

Hegel also believed that 'only the whole is true' and thus he was a forerunner of modern systems thinking. Holism is the epitome of systems thinking (Jackson, 2003). Holism argues that systems cannot be understood by Descartes' scientific reductionism (by dividing and examining component parts), because, it argues, the relationships between the parts, and their organisation, is often more important than the parts themselves. In short a system is more than a sum of its parts (Jackson, 2003).

Modern systems thinking is characterised by two interrelated disciplines 'hard systems thinking' and 'soft systems thinking'. Hard systems thinking is concerned with the behaviour of *physical* systems, which it describes in terms of 'elements, relationships, boundaries, inputs, transformations, outputs, environments, feedback, purpose, communication, hierarchies and control' (Jackson, 2000). By comparison 'soft systems thinking' is concerned with the behaviour of *human* systems. Soft systems thinking, otherwise known as 'the interpretive systems approach', puts people at the centre of the analysis, focussing on the perceptions, values, beliefs and interests of individuals (Jackson, 2000). Soft systems thinking was a development on 'hard systems thinking' in the 1980's, when it was recognised that hard-systems thinking wasn't suited to the purposive and pluralist nature of human activity systems (Jackson, 2003).

This research did not exploit any one systems research methodology, although Checkland's Soft-system methodology (SSM), which is reported to be the most popular and widely used application of Systems-Thinking (Mingers & White, 2010), was considered. This methodology was developed in response to a recognised need to be able to model human activity systems, in which purposeful actors with divergent views made it difficult to define problems let alone solve them (Mingers & White, 2010).

The core concern of SSM is to 'structure a debate' amongst people who perceive to themselves to have a stake in a problem and in doing so to identify possible improvements. Like other problem solving methodologies it focuses on surfacing and modelling underlying phenomena and looking for possible solutions emerging from the learning entailed. Despite its popularity the use of SSM as research methodology was considered inappropriate in this case for three reasons.

Firstly, at the outset of the case study, the problematic nature of the applied-innovation process in construction was not known nor could the importance of human actors in the design process be legitimately presumed. Use any problem structuring method to would have pre-supposed the implementation process to be something it was only latterly shown to be.

Secondly, the use of SSM as a mode of inquiry is an active-research approach and it was recognised that grafting this onto the real-world case study project would have put additional demands on the project team.

Thirdly, the inquiry process of SSM's strength is iterative tool, as Chekland (1995) describes 'you lean your way to relevance by going round the cycle, often many times in the course of the study'. The iterative nature of SSM was considered ill-fitting with the study of a longitudinal design process.

Finally, it was considered important that the results of the research were comprehensible in the context from which they originated, in this case a secondary school. De Bono's framework, based around hats of six colours, was recognised to be both more familiar in industry and an easier concept to grasp at a range of levels.

An interpretive soft systems approach was however adopted 'to get as close as possible to what was going on' (Jackson, 2000). Presupposing that there are multiple worldviews (Hegelian), based on taken-for-granted *a priori* assumptions (Kantian), the interpretive systems approach 'embraces subjectivity' (Jackson, 2000). This approach subscribes to Churchman's (1970) perspective that 'the only way we can get near to a view of the whole system is to look at it from as many perspectives as possible' in (Jackson, 2003). This research project approaches the design process from an interpretive paradigm, being concerned with the subjective points of view and intentions of those involved in the process (Jackson, 2000).

Elghali et al. (2008) argue that in complex contexts, the loss of certainty and the intrusion of ethics destroys the basis for a normal scientific approach. This portfolio combines findings of both normal and post-normal scientific research.

EXPLORATION

PART A: Lime-pozzolan concrete

Testing and development of a novel, low-CO_2 concrete based on hydraulic-lime and modern pozzolanic additions

Overview

As a vehicle for exploring the process of implementing innovative and sustainable materials in the construction industry, this EngD research programme principally comprised the development and specification of a novel, low-CO_2 concrete as a 'real-world' case study product. The objective of this tranche of the research was to investigate the feasibility of producing modern, sustainable hydraulic lime-pozzolan concretes with comparable strengths to Portland cement based concretes.

Section I of the thesis is a collection of papers, which collectively describe the scientific development of this novel concrete technology. Each paper is a standalone document typically written for a scientific audience and in the majority of cases peer reviewed by the academic community. As well as introducing each paper in turn, this section is provided to summarise the real-world story that contextualised and steered this research programme from the outset. Specifically three case study projects are introduced.

This industry-based academic research programme was contingent on the close collaboration between researchers and practitioners. On this basis it is held to be an example of Collaborative Practice Research (CPR), which Mathiassen (2002) promotes as an effective way of conducting research, arguing that it 'offers one practical way to strike a useful balance between relevance and rigour. In line with the core objectives of CPR, which focuses on 'improving the way in which we do research' (Mathiassen, 2002), this research and development project is itself a case study and this section concludes with a reflective evaluation of in the effectiveness of an industry based EngD in the development of an innovative construction material.

3 Introduction to PART A: Exploration

3.1 Initiation of the research project: An introduction to Case study project 1

In November 2008 Ramboll were contacted by an architectural practice, DSH architects, to enquire about the feasibility of building a doubly-curved shell roof from lime-concrete. DSH architects, who had been engaged to design an eco-house for a private client in the Cotswolds, envisaged an elliptical building with a turf covered, shallowly-domed roof, made from the limestone excavated from the site (see Figure 1).

Figure 1: Wickfield Lane House, architectural concept

The planning application for this new dwelling, which was located in an 'Area of Outstanding Natural Beauty' (AONB), fell within the restrictions of *Planning Policy Statement 7:Sustainable Development in Rural Areas* (PPS7) and as such the design had to be deemed 'truly outstanding or ground-breaking' (Office of the Deputy Prime minister, 2004). As a result the design included a number of innovative features, the chief one being the structural use of lime-concrete. The South-West design committee were recorded to have responded positively to the proposed use of suspended lime-concrete and suggested that this was indeed innovative enough to achieve PPS7 approval (Ramboll Whitbybird, 2008). Consequently the lime-concrete roof was not only integral to the architect's scheme design but also to the viability of client's proposed building project.

A local lime supplier 'The Traditional Lime Company', was also brought in as part of the research team. The architect was keen to manufacture the lime binder by firing limestone excavated from the site. Although The Traditional Lime Company had access to a steel kiln, where they fired lime putty not far from the site, they suggested that the most sensible approach was to use a manufactured lime product in combination with locally sourced aggregates. They agreed to supply lime for the material testing that was to be conducted in the Department of Architecture and Civil Engineering at the University of Bath.

The proposed lime-concrete roof structure was initially discussed at a pre-planning meeting, held at the University of Bath on the 21st November 2008 (Ramboll Whitbybird, 2008). The structural engineer Ramboll envisaged a 200mm thick lime-concrete shell, supported on a radial array of glue-laminated (glulam) beams, which would minimise the distance the lime-concrete slab above would span. Academics at the University suggested that a compressive strength of around 14N/mm^2 was feasible using lime, based on the work of Velosa and Cachim (2009). One academic expressly questioned the ecological benefits of using lime-concrete structurally, proposing that a thinner shell utilising Portland cement, the standard solution, might in actuality be less detrimental to the environment. This highlighted the importance of functional performance as a base line for comparing the embodied impacts of alternative construction materials (Purnell, 2011).

4 Background

4.1 Sustainable construction

The term ‘sustainability’ expresses the ability of one system to endure in the face of instability in interconnected systems. In the present anthropological context the term sustainability concerns the ability of human life to endure in the face of instability in the ecological, economic and social systems that underpin it. With planet earth supporting an unprecedented human population, society is living under the threat that collective human activity might be capable of upsetting the balance of the ecosystem that creates and sustains life on planet earth (Lovins et al., 2007).

Acceptance of the link between anthropogenic green-house gas emission and climate change, establishes a fundamental interconnectivity between human activity and the planet’s ecosystem. In the light of unprecedented population growth, extraordinary technological progress and extreme inequality in living standards, there is grave concern about the carrying capacity of planet earth as a finite system.

Sustainability is driving the research agenda in number of ways. Some researchers are seeking to prove the interoperability of human activity and ecological systems (Manuel-Navarrete et al., 2007, Rosenzweig et al., 2008); some to modelling the future scenarios based on a range of possible dependencies (Thomas et al., 2004, Sillmann and Roeckner, 2008, Patt et al., 2010) some are dedicated to delaying and minimising the impact of local or global system failure (McDaniels et al., 2008, Patt et al., 2010, Field et al., 2012); some are dealing with or diagnosing system failure (Forrester et al., 2005, Kates et al., 2006) and still others to designing future systems that reduce human impact and/or dependency on other systems (Coaffee, 2008, Dovì et al., 2009).

This research project falls within the final category and is concerned with the design and evaluation of a possible future ‘low-CO_2’ concrete technology. This potential technology aims to reduce the CO_2 emissions associated with the manufacture of cementitious-binders and thus seeks to disconnect construction activity with global warming. The link between anthropogenic CO_2-emissions and global warming is assumed and the value of this research is comprehended in this context.

Construction activity, as we know it, is highly unsustainable due to the harmful impact of the production, transportation and disposal of construction materials on the natural environment

(Lovins et al., 2007). At a global scale construction activity is thought to consume more than half the materials extracted from the earth every year (Purnell, 2011).

In the UK the construction industry is reported to consume over 420 million tonnes of construction materials per annum (Hammond and Jones, 2008) with around 20 million tonnes of construction, demolition and excavation waste going to landfill (Environment Agency, 2010). The industry is also reported to use around 8 million tonnes of oil and emit 29 million tonnes of CO_2 per annum (Hammond and Jones, 2008).

4.2 The search for low-CO_2 concretes

Concrete is the most widely used material on the planet after water (Sabir et al., 2001). In 2012 around 12 billion m^3 of concrete, or $1.7m^3$ for every man, woman and child on the planet, was produced. As the principal binding constituent of concrete, cement continues to be a key driving force of human development. In 2012 over 3.7×10^9 tonnes of cement were produced worldwide (U.S. Geological Survey, 2013). Global cement production is widely thought to be responsible for 5-9% of anthropogenic CO_2 emissions (Metz, 2007, Shi et al., 2011, Harrison, 2013) and 2-3% of primary energy use (Juenger et al., 2010). The production of cement is growing at a rate of 2.5% per year (Metz, 2007) driven by the increasing demand for concrete, which is acknowledged to be vital for meeting the basic needs of the global construction industry.

Concern about the harmful environmental impact of Portland cement manufacture on a global scale has prompted an extensive search for clinker replacement materials and alternative low CO_2 cements (LCC) that could succeed the current technology in time. With no other single technology promising to match the global availability and manufacturing efficiency of Portland-cement, a palette of prospective binder technologies are being developed (Shi et al., 2011). Collectively these new technologies constitute a second generation of cements, which are anticipated, in time, will usher in a more sustainable, post-Portland cement era.

Potential second-generation cements that are in different stages of research and development include: calcium sulfoaluminate cements (CSAC) (Ioannou et al., 2014), supersulfated cements (SCC) (Ioannou et al., 2013), alkali activated cements and geopolymers (Abora K, 2009), magnesium oxide cements (Liska et al., 2012), high volume slag cements (Saleh et al., 2012), and ternary cements (De Weerdt et al., 2011), as well as hydraulic lime-pozzolan cements (Grist et al., 2013). With a total installed capacity of 3.2 billion tonnes of clinker (Van Oss, 2013) and modern concrete construction practice entirely geared to the production and use of Portland cement, novel cements face a very difficult route to market. Commenting on emerging low CO_2 cements, Chana (2010) argued *"there is a future for new or novel cements…but there really is a long way to go before they can make substantial inroads into the market"* (Mineral Products Association, 2010). Rising fuel costs, CO_2 reduction targets and a growing demand for more sustainable alternatives are driving change and forward-thinking cement manufacturers are preparing to respond with new product technologies.

Amidst the development of radical new binder technologies there has been a resurgence of interest in Portland-cement's predecessor - lime, which, when produced at a large enough scale with the same production efficiencies as cement can, and in the case of some modern production facilities does (CESA, 2006), demand less energy and emit less CO_2 in manufacture. The laboratory research reported herein, focused on demonstrating the feasibility of producing a modern, structural-grade, hydraulic-lime concrete as a low-CO_2 alternative to Portland-cement concrete.

4.3 Literature review

4.3.1 History of lime-pozzolan concretes

An initial literature review was undertaken to identify previous research and knowledge in this area. Lime-pozzolan binders have a long history; a lime-concrete floor slab discovered in Southern Israel in 1985 was dated back to 7000BC (Bensted and Coleman, 2003). Hydraulic lime was the principal binder for use in construction (Kenny and Oates, 2000) until the advent of Portland-cement in the early 1800's. Although there is extensive historical precedence for lime-based concretes in construction (Holmes and Wingate, 1997), little research on the properties of hydraulic-lime binders has been undertaken since the work of Smeaton (1724-92) and Vicat (1786-1861). In the 1770's the civil engineer Smeaton conducted extensive testing on lime-pozzolan cements in a search for a suitable hydraulic cement for construction of the third Eddystone Lighthouse off the coast of Plymouth, UK. The mix Smeaton specified for this project consisted of blue lias slaked lime, pozzolanic trass and some copper slag (Bensted and Coleman, 2003).

The hydraulic lime-pozzolan concretes discussed in this thesis should not be confused with 'Limecrete' a commercially available lime-concrete suitable for low-grade structural applications. Rather, the potential use of lime-concrete as an alternative to Portland-cement concrete for structural components has been recognised, *'There is considerable potential for further research and development of lime concrete for its application as an appropriate* *building technology'* however it is acknowledged that, *'The science of using lime concrete in a similar way to Portland cement concrete for structural frames has not been developed'* (Holmes and Wingate, 1997).

Ten years after this knowledge gap was identified, one academic study investigated the mechanical properties of concretes made by combining natural hydraulic lime 5 (NHL5) with modern Type II additions familiar in modern concrete technology. Velosa and Cachim (2009) & Cachim et al. (2010) demonstrated that hydraulic lime-pozzolan concretes attained a 28-day cube strength of 11 MPa with 20% of the hydraulic lime replaced with a waste residue of expanded clay production and a maximum strength of 17 MPa with 20% of the hydraulic lime replaced with metakaolin, a calcined clay mineral. This study utilised materials available in Portugal and considering the feasibility of hydraulic lime-pozzolan concretes on a local scale.

Some initial work has also been conducted on the performance of limecrete-timber composites, but to date the limecrete toppings have had relatively poor mechanical properties (typically compressive strengths of 10-12MPa) (Hodsdon and Walker, 2006, Sebastian et al., 2010).

Bar the work of Velosa and Cachim (2009), the only research looking directly at the performance of alternative lime-concrete appears to be ad hoc trials conducted by lime-enthusiasts in response to project-specific enquiries, *'We have been playing with limecrete for the last few years…The first serious (well semi-serious) trials we did were as a result of an enquiry from a firm of Architects'* (Pritchett, 2001).

A decade ago, a review of 'industrially interesting approaches to "low-CO_2" cements', highlighted the potential for developing clinkers 'with a lower alite and higher belite content' (Gartner, 2004). Belite is notably the predominant hydraulic compound in hydraulic lime.

4.3.2 Lime-pozzolan binders

A recent guide on specifying sustainable concrete in the UK has recommended that to minimise the environmental impact of concretes, best practice is to use alumino-silicate by-products, such as silica fume, fly-ash and ground granulated blastfurnace slag, in combination with Portland cement to improve aspects of performance (Mineral Products Association, 2011). These mineral by-products, amongst others, which are classified as Type II additions, have been shown to enhance the properties of Portland-cement based concretes due to their pozzolanic or latent-hydraulic properties (Bye, 2011). The utilisation of pozzolanic materials in the production of cementitious binders is far from being a new practice and long pre-dates the invention of Portland cement. Prior to the advent of Portland-cement, the cementitious properties of naturally occurring pozzolanic materials were exploited in lime-based building materials for thousands of years.

The practice of 'gauging' limes mortars (and concretes) with pozzolanic materials, originated with the Greeks who utilized volcanic tuff (Blezard, 2000). The Romans similarly utilized the volcanic ash from Pozzuoli, at the base of Mount Vesuvius. The technique spread across Europe with the Roman Empire and continued throughout the middle ages. Where naturally occurring pozzolanic materials were not available, it was common practise to add ground up clay pots or broken roof tiles to create artificial pozzolanic materials suitable for hydraulic binders (Holmes and Wingate, 1997).

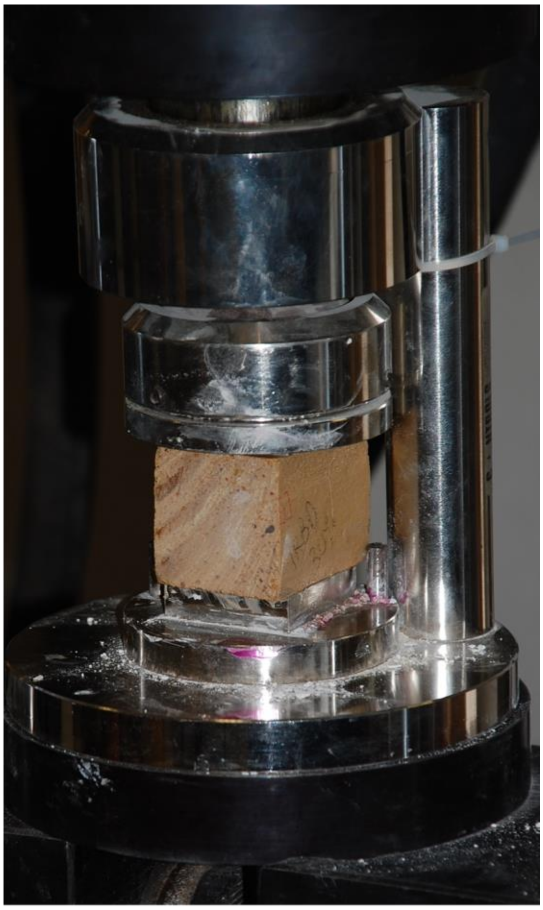
5 Research story

Given the paucity of research in this area, the technical feasibility of building a shallow lime-concrete dome was not known at the outset of the programme. Although compressive strengths of around 14 MPa were ostensibly attainable, it was recognised that the value of this novel solution, as a low-CO_2 alternative to Portland-cement, was contingent upon the structural capacity of this innovative material technology. For this reason a 28-day compressive strength of 30 MPa was deemed to be a minimum threshold for performance and the research set off in pursuit of exploring and maximising mechanical strength.

In the absence of a definitive source of information on hydraulic-lime binders prepared with natural or artificial pozzolanic materials, the initial phase of testing, which commenced in February 2009, was a systematic study of the mechanical properties of lime-pozzolan mortars. Driven by the anticipated implementation of the lime-pozzolan concrete technology being studied, the testing concentrated on the performance of commercially available aluminosilicate by-products and modern Type (II) pozzolanic additions. This study is described in Paper 1: Grist, E.R., Paine, K.A., Heath, A. and Norman, J., (2013). Compressive strength development of binary and ternary lime-pozzolan mortars. Materials and Design. 52:pp514-523. This paper considered the compressive strength development of broad range of hydraulic lime mortars prepared with a range of commercially available mineral additions. Lime-pozzolan mortars, as opposed to concretes, were produced and tested to minimise the use of materials. The aim of this preliminary laboratory research was to identify mineral additions, or combinations thereof, which when used in conjunction with hydraulic lime had the potential to attain compressive strengths in excess of 30MPa, when scaled up from mortars to concretes. The laboratory testing is depicted in Figure 2.

(a) Hydraulic lime-pozzolan mortar samples

(b) Water-curing of lime-pozzolan mortars



(c) Compressive strength testing

Figure 2: Lime-pozzolan mortar testing

The results showed that combining a natural hydraulic lime (NHL5) with silica fume and ground granulated blastfurnace slag could produce a ternary lime-pozzolan mortar with a 28-day compressive cube strength of around 28 MPa, at a water-to-binder (w/b) ratio of 0.5. This was eight times the strength of an equivalent mortar prepared with NHL5 alone and broadly speaking comparable with that of a low-heat of hydration cementitious mortar.

Analysis of the results allowed the pozzolanic additions, and combinations thereof, to be ranked from low to high efficacy. A ternary combination of SF and GGBS was shown to result in the greatest overall pozzolanic efficacy (%), attaining a maximum value of 94% at 28-days. The four most promising combinations of additions were identified and scaled up to lime-pozzolan concretes at the subsequent phase of testing.

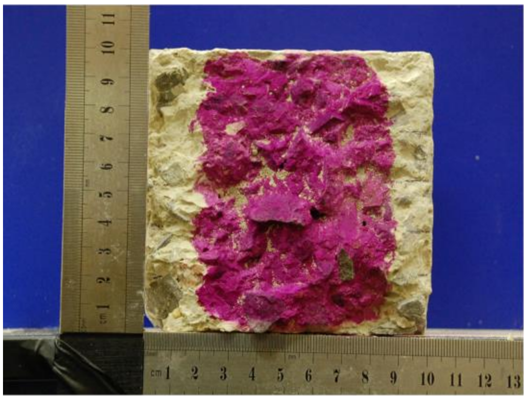
Having explored the mechanical strength of a range of lime-pozzolan mortars, the second phase of testing commenced in June 2009. This study is described in Paper 2: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). Structural and durability properties of hydraulic lime-pozzolan concretes, accepted for publication in Cement and Concrete Composites in January 2014. The aim of this study was to investigate the structural and durability characteristics of a small number of preliminary hydraulic lime-pozzolan concretes. A suite of tests were undertaken to ascertain the technical feasibility of producing high strength concretes using NHL5 and modern aluminosilicate by-products.

(a) Mix constituents

(b) Fresh lime-pozzolan concrete

(c) Lime-pozzolan concrete post compressive strength testing

(d) Elastic modulus testing



(c) Carbonation resistance testing

(c) Linear shrinkage testing

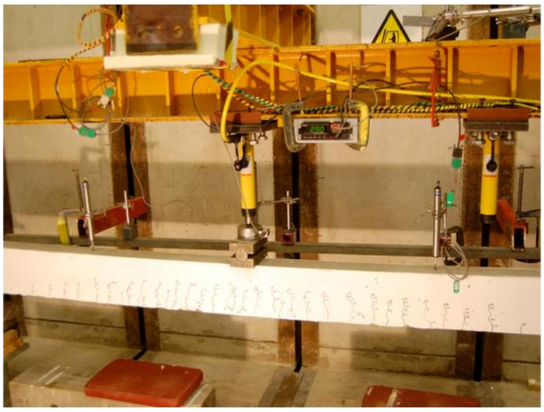
Figure 3: Phase two testing of hydraulic lime-pozzolan concretes

Specifically Paper 2 reports on the rate of strength development, elastic modulus, linear shrinkage and rate of carbonation of four hydraulic-lime-pozzolan concretes, testing which is depicted in Figure 3.

The results in Paper 2 were presented alongside comparable test results for Portland-cement (CEMI) and blastfurnace cement (CIII/A) concretes as a point of reference. Similarities and differences in material characteristics were discussed in terms of fundamental material properties and in terms of the emergent threats and opportunities for the potential development of these novel concretes. The results demonstrated that water-cured lime-pozzolan concretes could attain 28-day cube strengths of 35 MPa. These strengths make the material suitable for many structural applications.

The third phase of testing commenced in June 2010 and aimed at converging on a novel lime-pozzolan concrete mix-design appropriate for the roof of the eco-house. This study is described in Paper 3: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). Lime-pozzolan concretes: addressing project-specific questions, accepted for publication in Construction Building Materials in January 2014. Specifically this paper describes a sequence of laboratory tests that were undertaken to enhance the workability and hardened compressive strength development of a lime-pozzolan concrete, comprising a ternary combination of hydraulic lime, ground granulated blastfurnace slag and silica fume. This research demonstrated the feasibility of producing a lime-pozzolan concrete with a 28-day cube strength in excess of 45 MPa. When this concrete was cast into two steel reinforced beams the resulting structural elements were observed to have a finished appearance and flexural behaviour similar to Portland-cement concrete elements. Specific aspects of the performance of this novel concrete considered in this paper were; workability, binder composition, cold-weather curing and the flexural behaviour of reinforced lime-pozzolan concrete beams (see Figure 4.

(a) Effect of superplasticisers on flow



(b) Reinforced lime-pozzolan concrete beams

Figure 4: Phase three testing of hydraulic lime-pozzolan concretes

6 Real-world impact of the research

6.1 Case study project 1: Wickfield Lane House

The results of the laboratory testing reported in Paper 3 formed the basis of a structural appraisal report that was issued to the real-world project client in March 2011. In turn this report formed part of a planning application submitted to the Local Planning Authority (LPA) on the 17th May 2011. Two and a half months later, on the 2nd August 2011, planning permission for the proposed dwelling was refused. The lime-concrete was not mentioned on the decision notice; rather the decision was reported to have been made on the basis of the location, visual impact and proximity of the proposed dwelling to a Site of Special Scientific Interest (SSSI) (Tewkesbury Borough Council, 2011).

In January 2012 the client decided to appeal against the decision made by the LPA and the appellant's case was taken to the Planning Inspectorate. As part of this procedure Ramboll was engaged to undertake a full design of the lime-pozzolan concrete shell roof for a Building Regulations application. This included the production of a lime-concrete specification and a full calculation package. The building control submission was issued to the architect on the 27th January 2012.

The design was based on a characteristic lime-pozzolan concrete strength (f_k) of 34.5 MPa, which was determined in accordance with BS EN 1990:2002 + A1:2005, 2005 (2005), which details the appropriate statistical determination of strength bases on a limited number of strength tests, including that of new materials developed in the lab. A partial safety factor (γ_m) of 2 was adopted for the design. On this basis the calculated design strength f_{cd} of the novel lime-pozzolan concrete was 11.6 MPa. A conservative maximum strain value of 0.00231 (compared with a value of 0.0035 for the design of Portland cement structures) was also determined by the same statistical determination.

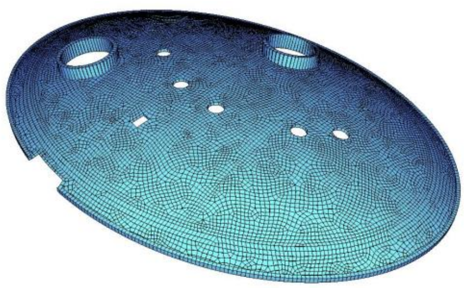


Figure 5: FEA model of lime-pozzolan concrete shell roof

The lime-pozzolan concrete roof shell (see Figure 5) was elliptical in plan spanning 29 metres in one direction and 22 metres in the other. The maximum rise in the centre was 2.7 m above the eaves. Circular openings for roof lights were punctured through the doubly curved shell structure. The 3D roof geometry was modelled in Rhino software and then a detailed finite element analysis (FEA) was performed in SOFISTIK to calculate maximum shear forces, bending moments and principal membrane forces in the shell (see Figure 6). The results were verified by comparison with a simplified hand analysis of a shallow circular dome, with a diameter equal to the average diameter of the elliptical roof plan. The FEA analysis was also used to calculate resulting deflections under serviceability loads, to perform a sensitivity analysis to the strength and stiffness of the lime-pozzolan concrete and to calculate the factor of safety against buckling under uniform and patterned loading arrangements.

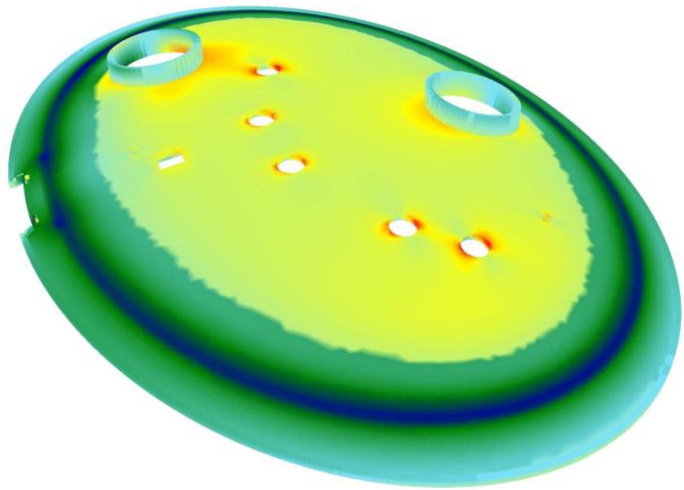


Figure 6: Stress distribution in lime-pozzolan concrete shell roof

The final shell was 200 mm thick with an A393 mesh reinforcement top and bottom and additional hoop reinforcement in the perimeter zone.

Because the creep behaviour of the novel lime-pozzolan concrete had not been determined in laboratory, a sensitivity analysis was performed to check the deflection of the shell in the instance of a substantial reduction in elastic modulus. With an assumed elastic modulus of 9 GPa (half the lowest elastic modulus of any lime-pozzolan concrete tested in the laboratory during the development of the new concrete), the maximum deflection was still permissible.

The lime-pozzolan concrete specification was in two parts. Part 1 was based on the National Structural Concrete Specification for Building Construction (CONSTRUCT, 2010) and Part 2 a summary of the results of the testing undertaken at the University of Bath. Building Control approval for the innovative structure was granted in March 2012 without any qualifications. This was third party validation of the innovative design.

In May 2012 Ramboll attended the planning appeal hearing having been invited by the client to present and defend the lime-concrete roof design. In this situation structural engineers from Ramboll were tasked with talking down any risks and presenting the design as infallible. Asked to sum up the lime-concrete research the client's planning officer is recorded to have said *'we have done extensive testing and are extremely confident'*. There was no forum for a dialogue about the inherent risks and how they were to be managed. Rather, in an attempt to add strength to their argument against the proposed project the Council was quick to pick the structural engineer up on the slightest utterance of 'risk'. This argument was quickly closed down when it was commented by another individual present that there is also a low-level of risk every time you step out of the front door. Taking an 'optimistic' line was found to be necessary in endeavouring to bring the innovative design to fruition.

The dialogue at the planning hearing about the risks associated with use of a novel concrete technology, was particularly revealing as one of the four 'concerned local residents' present, who strongly objected to the scheme on the basis that it 'contains substantial novel components' was a retired civil engineer 'with extensive experience of innovation and concrete design'.

Between the initial planning application and the planning appeal hearing the wording of PP7 had been changed from 'innovative *and* outstanding' to 'innovative *or* outstanding' (Office of the Deputy Prime Minister, 2004). The fact that the hearing ended with the planning officer commenting *'it all hinges on the limecrete then'*, was evidence of the importance of this technological innovation in the case of this project.

On 27th July 2012 the planning appeal was dismissed and the LPA's original decision to refuse planning permission for construction of the proposed lime-concrete eco-house was upheld. The Appeal Decision Notice was interesting with respect to the planning inspector's assessment of the novel lime-pozzolan or 'limecrete' structure:

'26. The use of limecrete as the main structural material in the form and scale proposed would undoubtedly be innovative. The development of an alternative material with a lower embodied carbon than concrete provides a very worthwhile objective.'

'27. Information given at the Hearing also went some way to address concerns about the untried nature of the material. The risk of it proving unequal to the task and resulting in the approved dwelling to be completed in a different, more conventional material now seems to be lower than feared by the Council. However, it appears that the Building Regulations approval obtained would leave that option open. While even a small element of risk remains, it would be more reasonable to develop the material in a project where the potential need to alter materials did not go to the heart of the justification for the approval of planning permission and where any learning benefit of the scheme could be delivered with greater certainty.'

'28. In any event, innovative designs would still be subject to the requirements of the Framework outlined above. As the design would not meet these requirements, the innovative nature of the material would not in itself justify approval of planning permission contrary to normal policy'.

This excerpt of the appeal decision notice (The Planning Inspectorate, 2012) provides evidence of the Planning Inspector's assessment of the innovative lime-concrete and the risks involved it implementing it for the first time. From this extract it can be gleaned that the planning officer believed the lime-concrete solution to be both *'innovative'* and *'worthwhile'*. The risk of the untried material at planning stage was evidently two fold; firstly there was a risk that the material could prove to be *'unequal to the task'* and secondly the risk that if it were unequal to the task that the project could still go ahead *'in a different, more conventional material'*. This extract also suggests that the Planning Inspectorate placed value on the learning opportunity that the project represented, as is it was noted *'it would be more reasonable to develop the material in a project…where learning benefit of the scheme could be delivered with greater certainty.'* Although this novel structural solution was considered innovative, this was *'not in itself enough to justify approval of planning permission contrary to normal policy'*. This planning decision closed the case study on the shell roof for the eco-house and changed the trajectory of the research. However, the decision was not reached until after an industrial trial with The Traditional Lime Company had been organised.

6.2 Industrial trial

The prospect of Wickfield Lane House, afforded the opportunity to undertake a small-scale industrial trial with the Traditional Lime Company – just (the decision to refuse the scheme planning permission was heard days before the planned trial, threatening to disrupt this opportunity). With plans and materials in place the trial went ahead on the 7th August 2012 with 0.165m^3 of lime-pozzolan concrete (approximately 400kg of materials) being manufactured in an industrial pan mixer by a small team of contractors (see Figure 7).

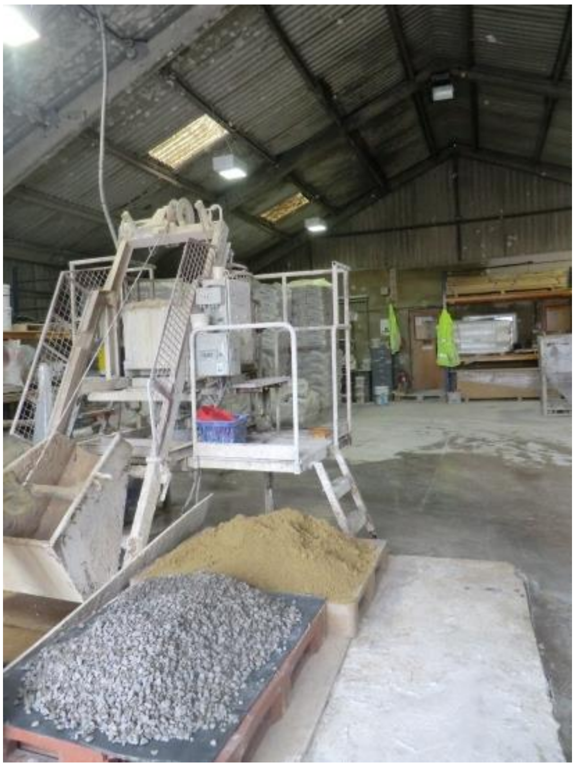


Figure 7: Industrial trial with The Traditional Lime Company

A new proprietary superplasticiser had been recommended by the chemical supplier for this industrial trial. This superplasticiser was specifically developed for the ready-mix industry and had better slump retention characteristics than the superplasticiser that had been used previously for the production of lime-pozzolan concretes in the laboratory.

This trial was itself a fascinating experience highlighting the differences between the production of materials in the laboratory and in the field. This quantity of lime-pozzolan concrete was observed to be too large for the mixer, which jammed causing great concern all round. Given the entire trial was recorded on a Dictaphone a transcribed excerpt of the dialogue is presented (see Figure 8) as a record of the event and evidence of the problematic nature of this trial. This story is included as it highlights the challenges associated with implementing innovation in the construction industry. Given that this trial was a negative experience for the contractor, *'my worst nightmare has happened'*, the risk is that it might have affected the propensity of those involved to undertake similar trials in the future.

#00:10:42-3# Mixer started (engine noise).

…10 minutes later there was a problem.

#00:20:46-6# Mixer shut off (engine noise stops).

#00:21:01-2# [Contractor A]: *Who has got that trowel there mind?*

#00:21:29-1# The noise of the switch being flicked on and off repeatedly.

#00:21:34-4# [Contractor A]: *Oh my worst nightmare has happened.* More switch flicking.

#00:21:42-1# [Contractor A]: *Right we'll run him backward for a second.* (Repeated efforts to get the mixer to turn).

#00:22:02-8# [Contractor A]: *Its jammed.* (More attempts to restart the engine)

… The problem was identified

#00:25:34-6# MG: *That is all the dry stuff in there? Apart from the (.) we didn't put the //* [Researcher]: *oh the slag // in there yet did we? I'm just thinking, as you say, do you think we can do it in two halves. I think it is just the sheer weight of it, it just can't shift in round. Because it is so dry.*

… Humour was used to try and downplay the problem

#00:27:06-8# [Contractor B]: *It is - it is just too much isn't it. I think Ellen has broken our machine.*

#00:27:12-1# [Researcher]: *Oh don't say that.*

#00:27:15-9# [Contractor B]: *That's okay, things break anyway. Everyday something breaks.*

#00:27:19-8# [Contractor A]: *We wanted a new one.*

#00:27:21-4# [Contractor B]: *Yeah* (laughter)

… The problem was resolved

#00:33:41-3# [Contractor C]: *Oh hang on lets give it a go. Stand well clear* (attempt to restart the machine). *Open him up* {Contractor A}. *You going to have to take a stack out.* (Attempt to restart*). It will go in a minute, I will tell you when.* (Attempt to restart). *Right shut him up.* (Mixer restarts).

#00:34:52-4# Noise of celebrating.

Figure 8: Excerpt of dialogue from the industrial trial

When the problem with the mixer had been overcome and the fresh lime-pozzolan concrete was thoroughly mixed it was cast into moulds, prepared with a light coating of mineral oil. Only during the casting did it transpire that an unknown volume of water had been added to the lime-pozzolan concrete mix with a hose, during the operation to restart the mixer. This was understandably the contractor's primary concern. The samples were then immediately covered in polythene and transported back to the laboratory at the University of Bath for controlled curing and testing. Samples were cured both in air and in water to assess the influence of curing on compressive strength development. Air-cured samples were cured in a conditioning lab maintained at 20±0.5°C and 60-65% RH. Water-cured samples were immersed in a water bath maintained at 20°C, in accordance with BS 12390-2 (2009).

With a new superplasticiser having been used for this trial and an unknown quantity of water added during the production process, it is not possible to explain the mechanical properties of the hardened lime-pozzolan concrete. The results were nonetheless still interesting as they demonstrated unprecedented mechanical strengths having been attained, and more importantly thus attainable, in the field. This material had an average 28-day cube strength of 39MPa when cured at 20±0.5°C and 60-65% RH and 57 MPa when cured in water maintained at 20°C, when measured in accordance with BS 12390-3 (2009). The strength development of the material is depicted in Figure 9.

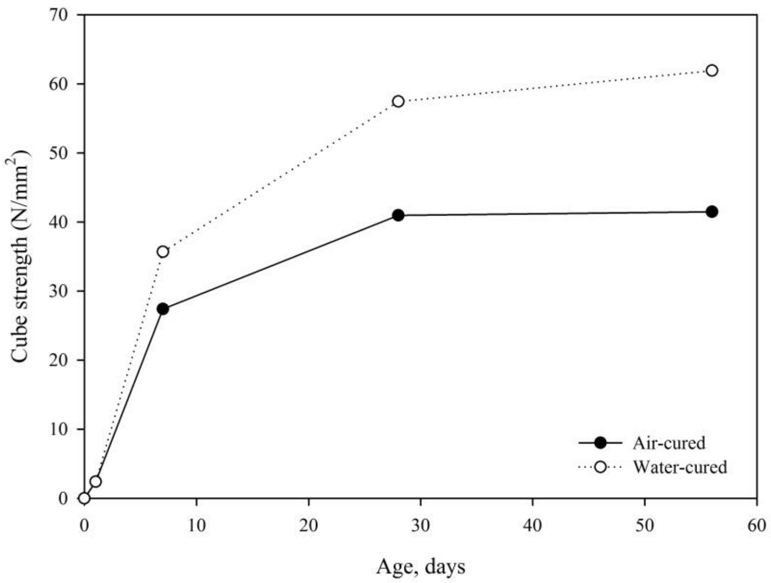


Figure 9: Strength development of a lime-pozzolan concrete produced in an industrial field trial

The results show that the lime-pozzolan concretes cured in water had a substantially higher compressive strength than those cured in air. Those samples cured in air were observed to have reached their maximum compressive strength at 28-days, whereas those samples cured in water continued to gain strength between 28-56 days.

The cylinder strength (f_{cyl}), elastic modulus (E_c), compressive strain at the maximum stress (ε_{c1}) and ultimate strain (ε_{cu1}) of the air-cured concrete was also determined at 28 days in accordance with BS EN 1881-121 (1983). The stress-strain plot for the lime-pozzolan concrete is shown in Figure 10.

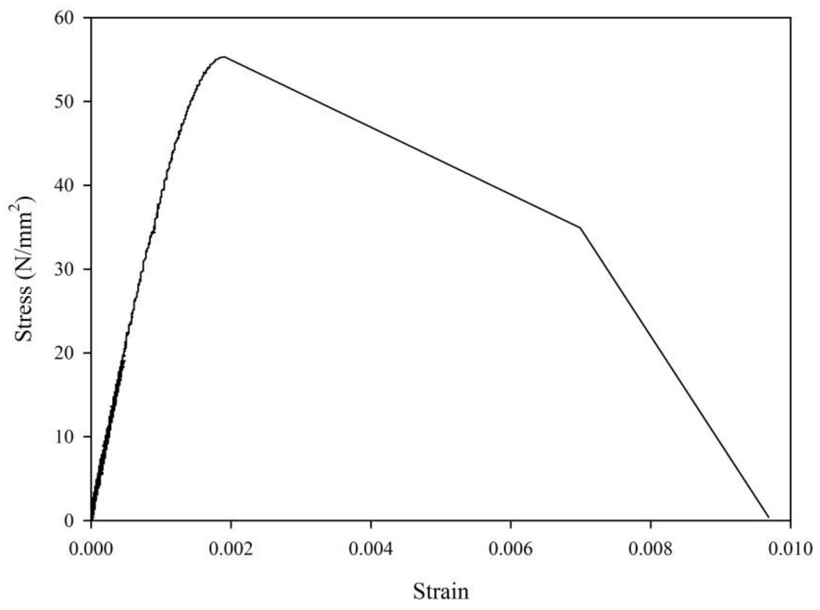


Figure 10: Stress-strain plot for the lime-pozzolan concrete produced in the field

This sample was subject to a peak stress of 55 MPa corresponding to a strain of 0.0019. The elastic modulus of this material was calculated as being 29 MPa. This is the highest mechanical performance of any lime-pozzolan concrete tested during this investigation. This performance might have been the result of using the contractor's aggregates, a w/b ratio of less than 0.35 (as a result of inadvertently using less water in the concrete mix than intended), enhanced performance contributed by the new superplasticisers or a combination of these three factors. Nonetheless, given the somewhat problematic nature of the production of this concrete, which might have been anticipated to compromise the performance of the material, these test results showed promise.

The industrial trial with Traditional Lime finally concluded this case study project and the research instead shifted towards a more generalised assessment of the viability and desirability of this novel concrete technology.

6.3 Dissemination of the research findings

Having demonstrated the potential for lime-pozzolan concretes in the laboratory and having lost the opportunity to implement the novel technology in the field, the next step was to begin disseminating the findings and soliciting feedback from a broader audience.

In May 2012, the first three phases of the laboratory testing were presented to the Society of the Chemical Institute (SOCI) in a paper entitled ‘Structural limecrete: an investigation into the potential of hydraulic lime-concrete using pozzolanic and latent hydraulic additions’. SCI Young Researcher Conference. Thursday 17 May 2012: London. This conference paper constitutes Paper 4.

The following month a further paper looking at the feasibility of this novel concrete technology was presented as part of the FIB Symposium ‘Concrete Structures for a Sustainable Community’. Paper 5 is the paper reproduced in the proceedings of this conference. Paper 5: Grist, E., Paine, K., Norman, J. and Heath, A., 2012. The feasibility and potential of modern hydraulic lime concretes. In: Concrete Structures for Sustainable Community, Fib Symposium, 2012-06-10 - 2012-06-14, Stockholm.

In March 2013 a paper considering the viability and benefits of modern hydraulic lime-pozzolan concretes was presented at the UKIERI Concrete Congress ‘Innovations in Concrete Construction’ in Jalandhar, India. Paper 6: Grist, E.R., Paine, K.A., Heath, A. and Pinder, H., 2013. An Investigation into the Viability and Benefits of Modern Hydraulic Lime Pozzolan Concretes. In: Dhir, R. K., Singh, S. P. and Goel, S., eds. Innovations in Concrete Construction. New Delhi: Excel India Publishers, pp. 967-981

This conference paper constituted a preliminary discussion on whether lime-pozzolan binders were environmentally sound, both in the short and long term. This theme was expanded in Paper 7: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). The environmental credentials of hydraulic-lime pozzolan concretes, accepted for publication in the Journal of Cleaner Production in December 2013**.** This paper additionally reports on the results of a laboratory study conducted to investigate the influence of the total binder content on the eco-efficiency of the resultant lime-pozzolan concretes. This journal paper focuses on the compressive strength, embodied CO_2, embodied energy and binder intensity of a range of ternary lime-pozzolan concretes and discusses whether lime-pozzolan concretes are a viable and desirable alternative to Portland cement concrete, particularly in the context of the industry wide search for low-CO_2 cements.

This study demonstrated that the use of aluminosilicate by-products, specifically ground granulated blastfurnace slag and silica fume, in combination with Natural hydraulic lime could realise savings in environmental impact, but that the potential savings are highly dependent on the boundaries of the analysis.

When calculating the embodied energy of blended cements incorporating aluminosilicate minerals that are by-products of other industrial processes, great care has to be taken in the collection and allocation of the data. Allocation is the methodology used to proportion life-cycle impacts, such as CO_2 emissions, between two or more co-products of a single manufacturing process.

This study demonstrated that the choice of allocation procedure would have a fundamental effect on the selection of the 'greenest' binder when comparing CEMI and lime-pozzolan concretes. Whereas in the case of GGBS it has been shown that economic allocation procedures maintain environmental benefits in comparison to CEMI, both mass and economic allocation procedures have a very detrimental effect on the environmental credentials of silica fume.

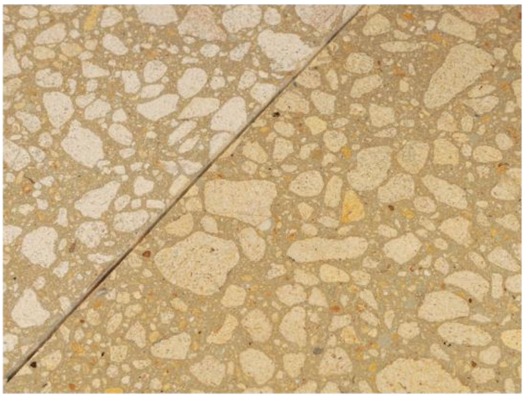
6.4 Case study project 2: A secondary school

In February 2011 Ramboll UK were appointed as structural engineers on a second 'real-world' project in which the client expressed an interest in utilizing the novel lime-pozzolan concrete. This case study project is described in Paper 8: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). Innovative solutions please, as long as they have been demonstrated elsewhere. Case Studies in Construction Materials Journal, January 2014.

Evolution of the scheme design in parallel with laboratory testing resulted in the development, and specification, of a polished lime-pozzolan concrete floor incorporating site-won oolitic limestone aggregate. Although there is little recent precedence for polishing lime-concrete floors, examples of this technique, such as the decorative terrazzo floor at the Villa Saraceno, Italy laid in 1612, provided historical precedence for this solution (Holmes and Wingate, 1997).

(a) Site-won frost shattered oolitic limestone

(b) Manual grading of site-won material



(c) Frost-shattered oolitic limestone aggregate

(d) Polished lime-pozzolan screed with site-won oolitic limestone aggregate

Figure 11: Development of a bespoke polished lime-pozzolan concrete screed using site-won oolitic limestone aggregate

In February 2012 a full specification for the innovative lime-pozzolan floor, which included all the laboratory test results, was issued to six contractors as part of the tender documentation at RIBA Stage D. A week, or so, after the lime-concrete specification was issued the local authority requested its withdrawal; they would not specify the innovative polished lime-concrete floor unless they could see it demonstrated in another school. This case study is expounded in Paper 8 (Grist et al., 2014) and in Section 2 of this thesis.

6.5 Case study project 3: Ecobuild March 2013

In March 2013 lime-pozzolan concretes were featured in the Future Materials Gallery at Ecobuild, the construction industry's major showcase of sustainable products and materials.

The aim of the new Future Materials Gallery was to bring together the world's latest building technologies in a futuristic showcase to educate and inspire the next generation of architects and designers. Under this umbrella, Ramboll took the opportunity to construct an interactive lime-pozzolan concrete installation to demonstrate this innovative material, whilst using the event to solicit immediate feedback on the future development and application of this technology.

The organisers of the gallery, a new feature for Ecobuild 2013, evidently appreciated the benefits of engaging with leading Universities and other organisations for they welcomed the demonstration of this technology at this event. Given this immature concrete technology was not in commercial production, the event organisers UBM were willing to waive the exhibitor fees (£422/m^2), which would normally be expected to prohibit new technologies from being shown at this high profile trade show.

Individuals from a total of fourteen organisations, spanning academia and industry, were brought on board to create this inspiring installation. Everyone approached was keen to be involved in this collaborative venture. A list of those involved is included in Table 1, which also outlines each party’s contribution to this installation. Brief extracts of initial email conversations had with each party, have been included as a way of illustrating the response of each party to this opportunity.

Table 1: Contributor involvement

Contributor	Contribution	Comments
University of Bath	Researcher Led Innovation Fund, additional grant funding & concrete cube testing at 7 and 21 days.	*'Yes, the department are keen to support this by contributing towards the cost'*
UBM (Ecobuild organisers)	Waiving the exhibitor fee. Receipt & storage of installation. Production of standardised information.	*'Yes, my colleague mentioned Ramboll might be providing material for the gallery, thank you very much!'*
Lazenby Contracts (contractor)	Fabrication of formwork. Casting of benches. Polishing of benches. Delivery of benches to the exhibition.	*'In principle we might be interested, but some detail of what it is you require will help us make the decision. Please can you let me have a proposal ASAP to see if we are able to help.'*
Hatcher Prichard (architect)	Design and sketch of benches (thought to have been critical in bringing on board Lazenby)	*'I regularly update our website and would love to pop a really short piece on about the benches if you feel it would be appropriate.'*
The Traditional Lime Company	Supply and delivery of NHL5	*'No problem regarding the two bags of NHL 5 – just let me know when you need them…Regarding Ecobuild, I will help in any way I can.'*
St Astier (supplier)	Manufacture of NHL5	*'I confirm that we will be supplying the material as requested. Please let me or Martin know where and when to deliver it.'*
Elkem (supplier)	Supply and delivery of SF	*'Happy to forward you your required sample…100kg delivered to?'*
Hanson (supplier)	Supply and delivery of GGBS	*'We thank you for opportunity to advertise our product on your stand at Ecobuild and plan to pop along to the event. I forwarded the sample request to our lab for processing last week and will be delivered to the Yeovil address.'*
BASF (supplier)	Supply and delivery of SP	*'I am sure BASF would be keen to be involved in something like this. I will pass it onto the relevant people at Manchester but in the meantime let me know what admixtures you need and I will get them sent down.'*
Ramboll	Bench reinforcement design and structural check. Design of supporting brochure. Production of web page. Design and printing of pull up banner. Printing of bench labels.	*'Suzanne looks after events and coordinates all related activities. She's back in the office on Monday 7th January.'*
WRAP	Contacts with secondary aggregate suppliers.	*'Hi Ellen, I suggest you have a word with…'*
Aggregate Industries (supplier)	Supply of recycled glass, stent sand and IBAA (only the glass was ultimately used).	*'Very interested Ellen… We can organise china clay sand and stent aggregate.'*
Raymond Brown Minerals & Recycling Ltd (supplier)	Supply of crushed demolition waste aggregates (3 sizes).	*'We would be pleased to partake in this project. We have washed recycled aggregates available from our Rookery farm site. These include sand, 10mm and 20mm.'*
EPSRC	Funded the EngD research.	

Two lime-pozzolan concrete benches were fabricated for this event in conjunction with a specialist-concrete contractor. The two lime-pozzolan concrete benches incorporated recycled aggregates, which were visible in the diamond polished seats. The benches, which were reinforced with A142 mesh and additional longitudinal bars (equivalent to 4no. H12 tension bars and 2no. H3 compression bars), were designed to demonstrate both the structural and aesthetic potential of this innovative technology.

(a) Industry casting of lime-pozzolan concrete benches

(b) Recycled post-consumer bottle glass seeded into the surface

(c) Formwork being struck

(d) Lime-pozzolan concrete with crushed demolition waste aggregate

Figure 12: Production of polished lime-pozzolan concrete benches with specialist contractor

Showcasing this new material in this gallery proved to be a fantastic opportunity for a bi-directional exchange of knowledge about the potential future use of hydraulic lime-concrete. It was also an interesting experience to be repeatedly asked to 'sell' the material, an unfamiliar experience for an academic researcher. Architects, contractors, product designers, developers and home owners all expressed an interest in this new low-CO_2 technology.

Figure 13: Lime-pozzolan concrete showcased at Ecobuild, 2013

The challenge of demonstrating new materials in a trade show environment was found to be communicating to delegates that these innovative materials are pre-production. Much of the follow up to this exhibition involved managing the expectations of those interested in specifying the technology.

> *'We are interested in your products, after seeing them at Ecobuild, and were wondering if we could receive a sample of Lime-Pozzolan concrete. We particularly like the version where you used waste glass from industry to create a terrazzo like finish.'* Architect, 08.03.13

To which Ramboll replied:

> *'Please can I take this opportunity to reiterate that this lime-concrete, on show in the Future Material Gallery, is not yet a commercially available technology. Neither Ramboll, Lazenby or any other individual party are in a position to supply lime-concrete as a 'product'. This is not saying that it unfeasible to use it, but just to manage your expectations with regard to the supply of this new technology.'*

7 Overview of the research approach

Distinct from the traditional model of materials research, which is characteristically knowledge-driven, this research was characteristically performance-driven. This collaborative-practice research approach led to convergence on three workable solutions for three real-world projects, each with different requirements. Between projects the focus of the research shifted towards a more generalised assessment of the merits and potential application of the developing technology.

Firstly, laboratory testing was undertaken to investigate the feasibility of a structural strength concrete based on lime as a ‘green’ alternative to Portland-cement concrete for the roof of an Eco-house. Secondly the lime-pozzolan concrete was adapted to be appropriate for polished floor screed incorporating site-sourced aggregates. Thirdly the chance to showcase the innovative technology at Ecobuild created the opportunity to mix and place lime-pozzolan concretes in conjunction with a specialist concrete contractor.

This description of the research story is given here to contextualise the scientific inquiry, which is reported in detail across the eight papers that follow.

8 Lime-pozzolan concrete papers

Paper 1: Grist, E.R., Paine, K.A., Heath, A. and Norman, J., (2013). **Compressive strength development of binary and ternary lime-pozzolan mortars**. Materials and Design. 52:pp514-523

Paper 2: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). **Structural and durability properties of hydraulic lime-pozzolan concretes**. Accepted for publication in Cement and Concrete Composites. January 2014.

Paper 3: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). **Lime-pozzolan concretes: addressing project-specific questions**. Accepted for publication in Construction Building Materials. January 2014.

Paper 4: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2012). **Structural limecrete: an investigation into the potential of hydraulic lime-concrete using pozzolanic and latent hydraulic additions**. SCI Young Researchers Conference. Thursday 17 May 2012: London.

Paper 5: Grist, E., Paine, K., Norman, J. and Heath, A., 2012. **The feasibility and potential of modern hydraulic lime concretes**. In: Concrete Structures for Sustainable Community, Fib Symposium, 2012-06-10 - 2012-06-14, Stockholm.

Paper 6: Grist, E.R., Paine, K.A., Heath, A. and Pinder, H., 2013. **An Investigation into the Viability and Benefits of Modern Hydraulic Lime Pozzolan Concretes**. In: Dhir, R. K., Singh, S. P. and Goel, S., eds. Innovations in Concrete Construction. New Delhi: Excel India Publishers, pp. 967-981

Paper 7: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). **The environmental credentials of lime-pozzolan concretes**. Accepted for publication in the Journal of Cleaner Production. January 2014.

Paper 8: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). **Innovative solutions please, as long as they have been demonstrated elsewhere**. Case Studies in Construction Materials. 1 (2014) 33–39

Grist, E.R., Paine, K.A., Heath, A. and Norman, J., (2013). **Compressive strength development of binary and ternary lime-pozzolan mortars**. Materials and Design. 52:pp514-523

8.2 PAPER 2: Structural and durability properties of hydraulic lime-pozzolan concretes

E R Grist[a,b], K A Paine[b], A Heath[b], J Norman[c], H Pinder[a]

a. Ramboll, 40 Queen Square, Bristol, BS1 4QP, UK
b. University of Bath, Claverton Down, Bath, BA2 7AY, UK
c. University of Bristol, Bristol, BS8 1TR, UK

Abstract

This paper discusses the results of a suite of tests designed to assess the structural and durability characteristics of hydraulic lime-pozzolan concretes. Specifically this paper reports on the rate of strength development, elastic modulus, linear shrinkage and rate of carbonation of four hydraulic-lime-pozzolan concretes. The purpose of this investigation was to ascertain the technical feasibility of producing high strength concretes using hydraulic lime and pozzolans as an alternative binder to Portland cement. Results have demonstrated that 28-day cube strengths of 35 MPa can be attained by water-cured lime-pozzolan concretes. These strengths make the material suitable for many structural applications.

The results are presented alongside comparable test results for Portland-cement (CEM I) and blastfurnace cement (CEM III/A) concrete as a point of reference. Similarities and differences in material characteristics are discussed in terms of fundamental material properties and in terms of the emergent threats and opportunities for the potential development of these concretes.

Key words: *Hydraulic lime concrete, pozzolan, compressive strength, curing, durability*

Introduction

Concern about the harmful environmental impact of Portland cement manufacture on a global scale has prompted an extensive search for clinker replacement materials and alternative low carbon cements (LCC) that could succeed the current technology in time. Global cement production exceeds 3.4 x 10^9 tonnes per annum [1] and is widely thought to be responsible for 5-9% of anthropogenic carbon emissions [2], [3], [4] and 2-3% of primary energy use [5]. The production of cement is growing at a rate of 2.5% per year [2] driven by the increasing demand for concrete, which is acknowledged to be vital for meeting the basic needs of the global construction industry.

With no other single technology promising to match the global availability and manufacturing efficiency of Portland-cement, a palette of prospective binder technologies are being developed [3]. Collectively these new technologies constitute a second generation of cements, which will usher in a more sustainable post-Portland cement era. Amidst the development of radical new binder technologies there has been a resurgence of interest in Portland-cement's predecessor - lime, which, when produced at a large enough scale with the same production efficiencies as cement can, and in the case of some modern production facilities does [6], demand less energy and emit less carbon dioxide in manufacture.

A recent guide on specifying sustainable concrete in the UK has recommended that to minimise the environmental impact of concretes, best practice is to use alumino-silicate by-products, such as silica fume, fly-ash and ground granulated blastfurnace slag, in combination with Portland cement to improve aspects of performance [7]. These mineral by-products, amongst others, which are classified as Type II additions, have been shown to enhance the properties of Portland-cement based concretes due to their pozzolanic or latent-hydraulic properties [8]. The utilisation of pozzolanic materials in the production of cementitious binders is far from being a new practice and long pre-dates the invention of Portland cement. Prior to the advent of Portland-cement, the cementitious properties of naturally occurring pozzolanic materials were exploited in lime-based building materials for thousands of years.

Despite a long and rich history of lime-concrete in construction, little research on the properties of hydraulic-lime concretes has been undertaken since the work of Smeaton (1724-92) and Vicat (1786-1861). The potential use of lime-concrete as an alternative to Portland-cement concrete for structural components has been recognised, but it is acknowledged that 'the science has not been developed' [9]. Ten years after this knowledge gap was identified, work in this area began by considering the mechanical properties of concretes made by combining NHL5 (Natural Hydraulic Lime with a 28-day compressive strength ≥ 5 MPa in accordance with BS EN 459 [9(a)] with modern Type II additions familiar in modern concrete technology. Specifically Velosa and Cachim [10] & [11] demonstrated that hydraulic lime-pozzolan concretes attained a 28-day cube strength of 11 MPa with 20% of the hydraulic lime replaced with a waste residue of expanded clay production and a maximum strength of 17 MPa with 20% of the hydraulic lime replaced with metakaolin, a calcined clay mineral.

For lime-based concretes to be a legitimate alternative to a cement-based concretes they must be capable of performing the same function, for at least as long, without any additional increase in overall binder content or total concrete volume. Although a low strength material might find some limited application a cube strength of at least 30 MPa, comparable with that of a low-strength cement-based concrete, is considered a minimum performance threshold. Initiated by the desire of a UK architect to build a doubly-curved shell roof for an eco-house using lime-concrete, this experimental investigation has built on the work of Velosa and Cachim [10] & [11] and focused on the strength and durability characteristics of a range of potential lime-pozzolan concretes believed to have the capability to attain compressive strengths suitable for modest structural applications.

A preliminary investigation into the strength development of hydraulic lime mortars demonstrated that it is feasible to produce high-strength lime mortars, with a comparable 28-day compressive strength to Portland cement mortars, by combining lime with alumino-silicate materials, many of which are by-products of other industrial processes. Tests conducted at a mortar scale were a precursor to the work reported herein and were aimed at identifying a small number of lime-pozzolan blends with the potential to produce a structural grade material when scaled up to lime-pozzolan concretes [12]. This paper reports on the mechanical properties of four hydraulic lime-pozzolan concretes; binary and ternary combinations of NHL5, silica fume (SF), metakaolin (MK), ground granulated blastfurnace slag (GGBS) and fly ash (FA).

Materials and methods

The experimental programme comprised the production, curing and testing of four lime-pozzolan concretes, denoted (I)-(IV). Each binder was a binary or ternary combination of NHL5 and alumino-siliceous mineral additions. Identification of these four combinations was the primary objective of an earlier study looking at the pozzolanic efficacy of different compositions and is described elsewhere [12].

70% NHL5 with 15% FA & 15% MK (I)

50% NHL5 with 25% SF & 25% GGBS (II)

70% NHL5 with 30% SF (III)

50% NHL5 with 25% SF & 25% FA (IV)

A suite of experiments was used to assess the structural and durability characteristics of the hardened lime-pozzolan concretes.

In this paper the results are typically compared with two reference concretes: a CEM I concrete and a 50% PC & 50% GGBS concrete (CEM III/A). CEM III/A concretes are routinely specified in the UK and this particular CEM III/A mix had 47% lower embodied CO_2 than the CEM I, based on calculations described in Mason et al (2011) [21], and thus is considered an appropriate baseline for performance in the development of alternative low carbon cements. The CEM I and CEM III/A concretes were prepared and tested, concurrently with the lime-pozzolan concretes according to the standard procedure outlined ~~above.~~

Materials

The NHL5 used was a natural hydraulic lime manufactured in France and supplied by a specialist lime-building merchant in the UK. The SF was obtained in the form of a slurry, with a SF:water ratio of 50:50 by mass, and conformed to BS EN 13263 [13]. The GGBS and FA conformed to BS EN 15167 [14] and BS EN 450 [15] respectively. A proprietary metakaolin, from France, was also used. This specific product was found to be the most favourable of three alternative metakaolins utilised in the earlier lime-pozzolan mortar study. The major oxide compositions of these materials are shown in Table 2.

Table 2: Properties of constituent materials

	NHL5	SF	GGBS	FA	MK
Oxide analysis (% by weight)					
SiO_2	15.0	94.5	33.0	53.0	55.0
Al_2O_3	1.9	0.3	14.0	30.0	39.0
$K_2O + Na_2O$	0.3	1.3	0.8	0.7	1.0
Fe_2O_3	0.6	0.3	0.4	7.0	1.8
TiO_2	0.2	0.0	0.0	1.5	1.5
CaO + MgO	60.0	0.8	47.0	4.0	0.6
Physical properties					
BET specific surface area (m^2/kg)	800	22,000	2,650	4,090	19,000

Although in the UK a water content of 175 litres/m^3 is typically used to produce concrete of average consistence [16], a free water content of 240 litres/m^3 was initially selected due to the high surface area of the hydraulic lime, pozzolans and the coarse aggregate, a 10-14 mm carboniferous limestone. The particle size distribution (PSD) of the coarse aggregate was determined in accordance with BS 933-1:2012 [17] and is shown in Figure 14.

All the aggregates were dried under ambient conditions in the laboratory for at least 24 hours prior to use to ensure they were consistently in a lab-dry state. The coarse aggregates were assumed to have an absorption coefficient of 0.6%. The total water content was corrected accordingly, to allow the aggregate to achieve a saturated surface-dry condition before mixing whilst maintaining the desired effective water content

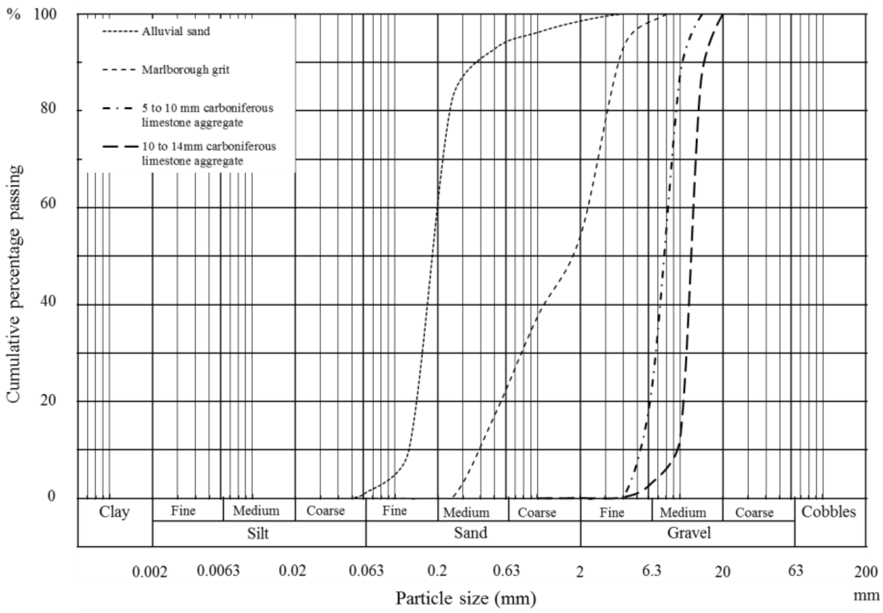


Figure 14: Particle Size Distribution [PSD] of the aggregates

The fine aggregate was 50% Marlborough grit and 50% alluvial sand by weight. The particle size distribution of these fine aggregates was determined in accordance with BS 933-1:2012 [17] and is also shown in Figure 14.

Mix design

Each of the four lime-pozzolan concretes was prepared at three discrete water-to-binder (w/b) ratios in order to assess the effect of the w/b ratio on the resulting properties of the hardened material. To account for the varying densities of the alumino-silicate additions utilised in the four mixes, an additional measure of fine building sand was calculated in each case to bring the resulting volume up to one cubic metre. The Building Research Establishment's (BRE's) mix design process for concrete [18] was used as the basis for proportioning aggregates. The required volume of material for each batch was calculated based on the total volume of all the test samples plus an additional 10% for losses. Details of the mix constituents are presented in Table 3.

Table 3: Mix constituents

Mix description	NHL5	SF	GGBS	FA	MK	**Total binder**	Water	5-10mm	10-14mm	Alluvial sand	Marlborough grit	w/b	Density
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3		kg/m^3
70% NHL5, 15% FA & 15% MK (I)	480	-	-	103	103	**686**	240	430	602	148	148	0.35	*2253*
	336	-	-	72	72	**480**	274	460	644	220	220	0.57	*2298*
	259	-	-	56	56	**371**	240	465	651	273	273	0.65	*2272*
50% NHL5, 25% SF & 25% GGBS (II)	343	171	171	-	-	**685**	378	430	602	150	150	0.55	*2395*
	240	120	120	-	-	**480**	316	460	644	223	223	0.66	*2345*
	185	93	93	-	-	**371**	240	465	651	273	273	0.65	*2272*
70% NHL5 & 30% SF (III)	480	206	-	-	-	**686**	240	430	602	138	138	0.35	*2233*
	336	144	-	-	-	**480**	266	460	644	213	213	0.55	*2275*
	259	111	-	-	-	**370**	240	465	651	268	268	0.65	*2261*
			-	-	-								
50% NHL5, 25% SF & 25% FA (IV)	343	171	-	171	-	**685**	274	430	602	128	128	0.40	*2246*
	240	120	-	120	-	**480**	274	460	644	205	205	0.57	*2268*
	185	93	-	93	-	**371**	240	465	651	263	263	0.65	*2252*

Experimental procedures

This section outlines the suite of experiments that was used to assess the structural and durability characteristics of the hardened concretes tested in this work. The concretes were prepared in a rotary pan mixer according to BS 1881-125:1986 [19] and then cast and cured in accordance with the relevant standards, as detailed below.

Compressive strength development

To investigate the compressive strength development of the four concretes, a total eighteen 100mm cubes were cast, in accordance with BS EN 12390-2:2009 [20], for each binder. To assess the influence of curing conditions on the compressive strength development of lime-pozzolan concretes, half the cubes were cured in air and half in water. In both cases the cubes were covered in a sheet of polythene for 24 hours before demoulding, at which point they were divided into two equal groups for curing. Air-cured cubes were cured in a conditioning lab maintained at 20±0.5°C and 60-65% RH. Water-cured cubes were immersed in a water bath maintained at 20°C. The cube strength of these concretes was determined in accordance with BS 12390-3: 2009 [22] at 7, 28 and 56 days. Both air and water cured specimens were tested straight from their respective curing conditions, without any wetting or drying.

Elastic modulus

A total of four cylinders were cast for determining the static modulus of elasticity of the lime-pozzolan concretes in accordance with the method described in BS1881-121:1983 [29]. The static modulus of elasticity in compression of the lime-pozzolan concretes was determined following 90 days of continuous moist curing rather than the specified 28 days. In accordance with the procedure the compressive strength of each concrete was first determined from the 90-day cube strength of three samples cured in the same conditions.

Carbonation resistance

The accelerated carbonation test procedure was based on a draft EN standard [34]. For each batch, one 100x100x400mm prism was cast and de-moulded after 24 hours. The specimens were cured in a water bath for 14 days followed by 14 days at 20±0.5°C and 60-65% RH. After a total of 28-days curing the top, bottom and two side faces of each specimen were sealed with two coats of paraffin wax, to prevent the ingress of gaseous CO_2. The specimens were then transferred to a chamber with active control of the temperature and concentration of atmospheric CO_2. The temperature was maintained at 20°C and the concentration of CO_2 at 4%. The relative humidity of the chamber was maintained around 60% using a tray of saturated sodium bromide solution [35]. When analysing the results it was conservatively assumed that 1 week in the carbonation chamber was equivalent to 1 year of exposure to the atmosphere, in line with the work of others [36] & [37]. At 14 day intervals a 50mm slice of the specimen was sampled using a bolster and chisel. The split end of the remaining specimen and any damage to the paraffin wax was then immediately resealed and the sample returned to the chamber.

The split surface of each slice was treated with a standard phenolphthalein indicator solution [38]. After one hour the depth of the carbonation front was measured using callipers. The distance between the characteristic pink stain of the indicator solution, and the outside edge of the exposed surface was read at ten discreet intervals along the edge from which an average carbonation depth was calculated.

Linear shrinkage

Linear shrinkage measurements were performed using a vertical comparator in accordance with ISO/DIS 1920-8 [45]. A total of twelve 75x75x280 mm prisms were stored at 20±0.5°C and 60-65% RH, the controlled conditions available, and the precise mass and length of each sample was measured and recorded at periodic intervals over a twenty week period.

Results and discussion

Compressive strength development

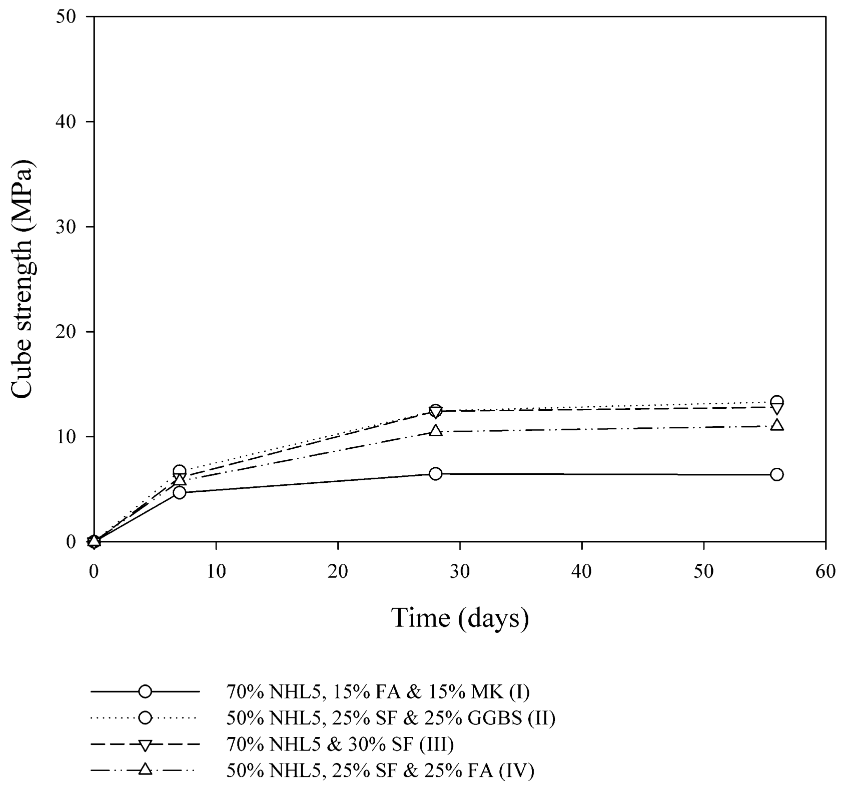
Table 4 gives the mean compressive strength of the lime-pozzolan concretes tested at 7, 28 and 56 days, for both water- and air-cured specimens. The mean compressive strength of the dry-cured samples is also presented as a percentage of the mean compressive strength of equivalent wet-cured samples.

Table 4: Compressive strength development of hydraulic lime-pozzolan concretes (MPa)

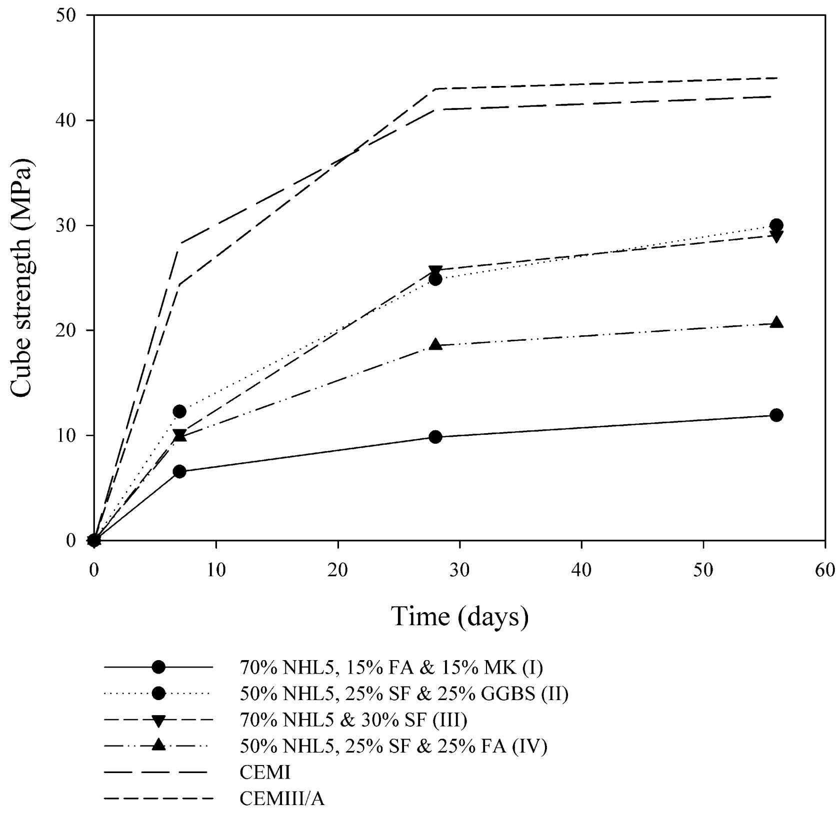
		Air-cured (20°C, 65% RH)			Water-cured (20°C, 100% RH)			Air/Water (%)		
	Age	7	28	56	7	28	56	7	28	56
Composition	*w/b*									
70% NHL5, 15% FA & 15% MK (I)	*0.65*	4.7	6.5	6.4	6.5	9.8	11.9	71%	66%	54%
	0.57	9.6	11.2	11.4	14.0	20.5	21.7	69%	55%	52%
	0.35	10.6	12.6	12.4	17.8	23.1	24.1	60%	55%	51%
50% NHL5, 25% SF & 25% GGBS (II)	*0.79*	4.9	7.5	7.1	7.3	19.4	22.6	67%	38%	31%
	0.66	6.7	12.5	13.3	12.3	24.9	30.0	55%	50%	44%
	0.55	7.7	13.4	13.5	13.5	30.5	34.3	57%	44%	39%
70% NHL5 & 30% SF (III)	*0.65*	6.1	12.4	12.8	10.2	25.8	29.1	60%	48%	44%
	0.55	9.5	16.2	16.3	14.3	29.0	31.6	66%	56%	52%
	0.35	12.7	21.5	22.8	21.4	35.7	37.5	59%	60%	61%
50% NHL5, 25% SF & 25% FA (IV)	*0.65*	5.8	10.5	11.0	9.8	18.5	20.6	59%	56%	53%
	0.57	7.5	13.9	14.2	12.4	21.7	22.0	60%	64%	64%
	0.40	11.6	21.2	21.4	17.0	31.3	32.9	68%	68%	65%

The maximum 28-day compressive strength of the four lime-pozzolan concretes was 35.7 MPa; a strength attained by combining NHL5 (70% by mass) with silica fume (30% by mass) and curing the resulting concrete in water. The 28-day cube strength of the equivalent air-cured concrete was 21.5 MPa, 40% lower. Three of the lime-pozzolan concretes (II), (III) and (IV) attained a 28-day cube strength greater than 30 MPa, the minimum performance threshold identified, when cured in water but none achieved this strength when cured in air. This shows that hydraulic reactions govern early-age strength and that the carbonation of lime is of less importance.

Figure 15 shows the comparative strength development of the four concretes, for both air- (a) and water –cured (b) samples, at a w/b ratio of 0.65.



(a)



(b)

Figure 15: Strength development of (a) air- and (b) water-cured lime pozzolan concretes [w/b = 0.65]

The rate of compressive strength development of the two strongest lime-pozzolan concretes was almost identical for both air- and water-cured specimens, see Figure 15 (a) & (b). The lime-pozzolan concrete with the lowest compressive strengths incorporated 15% FA & 15% MK. The order of the strength of the concretes is unaffected by the curing regime, however the two plots clearly show that curing conditions have a substantial effect on the strength development of lime-pozzolan concretes. An increased sensitivity to curing conditions might be expected as a result of the slower hydration of belite reaction, which would be inhibited to a greater extent by the evaporation of the free-water from the capillary pores in dry-curing conditions. Certainly in Portland-cement concretes it has been observed that the degree of hydration of alite, cured in water for seven days and then cured in air, varied only marginally from alite cured continuously in water. Conversely, that the hydration degree of the belite was substantially affected by the change in curing conditions [23].

Furthermore the results show that the sensitivity of hydraulic lime-pozzolan concretes to sub-optimal curing conditions is affected by the inclusion of different alumino-silicate additions.

At 28-days the lime-pozzolan concrete prepared with FA and MK was the least affected by dry-curing (44% reduction), whereas the lime-pozzolan concrete prepared with SF alone was most affected (52% reduction) at a w/b ratio of 0.65.

Strength development in comparison with Portland-cement concretes

Having considered the effect of curing conditions on the strength gain of lime-pozzolan concretes, it is valuable to compare the cube strengths attained with those of the two reference PC-concretes. Figure 15 (b) shows the strength development of water-cured lime-pozzolan concretes in comparison with two water-cured reference concretes prepared using the same aggregates and at the same w/b ratio. Figure 15 (b) clearly demonstrates that the compressive strength of all four of these lime-pozzolan concretes is substantially lower than that of the cement-based concretes. However the difference beween the strengths of these two alternative concrete-systems is shown to dimish over time. A number of interesting features can be observed from inspection of this Figure.

The rate of strength gain between 7 and 28 days is similar for lime-pozzolan concretes (II) and (III) in comparison to the reference PC concretes. For these two lime-pozzolan concretes the lower 28-day compressive strengths can be attributed to the lower 7-day strengths.

The reduced compressive strength in lime-pozzolan concretes, in comparison to PC concretes, is most significant at early ages (less than 7 days) when pozzolanic reactions are in their infancy.

In all four of the lime-pozzolan concretes the rate of strength gain between 28 and 56 days is greater than it is in the PC systems, which are observed to plateau after 28 days. This is consistent with the slower hydration of belite (C_2S).

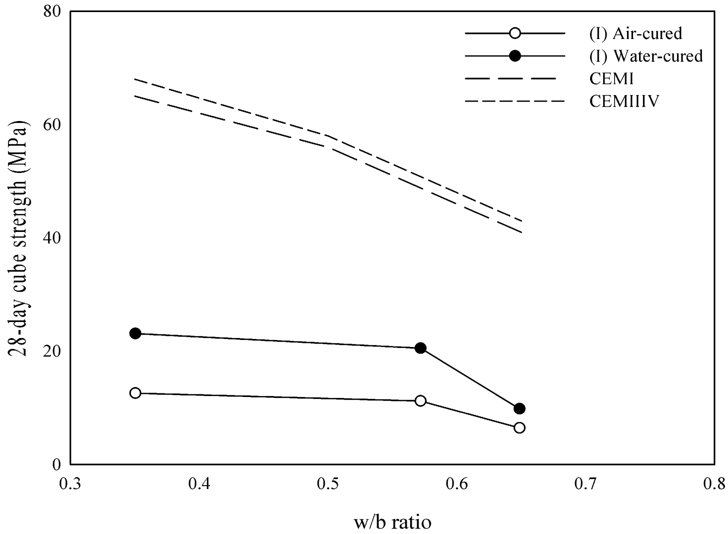
Further physio-chemical analysis is needed to describe the nature and progress of mechanism by which this lime-pozzolan concrete develops mechanical strength in alternative curing conditions.

Long term strength development

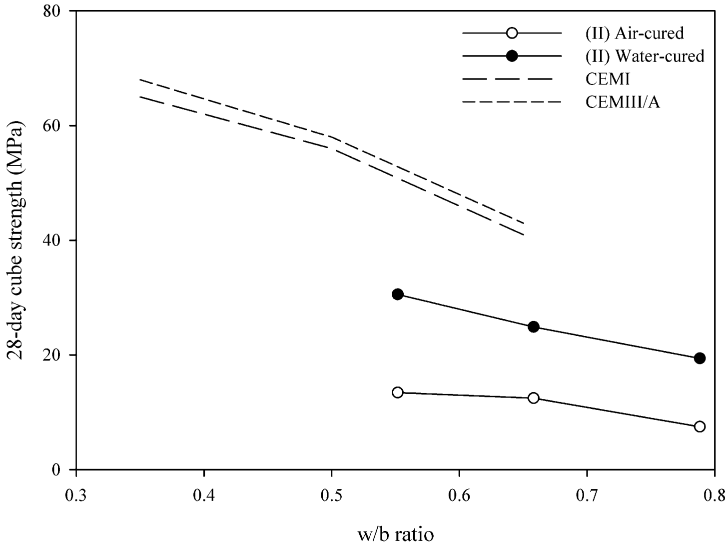
An area of future interest in the development of lime-pozzolan concretes is long-term strength development. Preliminary studies suggest a substantial strength gains may be attained between 90 and 1000 days when lime-pozzolan concretes are cured continuously in water.

Relationship between w/b ratio and strength

The relationship between w/b ratio and strength for the four concretes indicates the potential for producing higher strength lime-pozzolan concretes at lower w/b ratios. Figure 16 shows the relationship between w/b ratio and compressive strength for each of the four lime-pozzolan concretes in comparison to corresponding results for the two reference PC-concretes.



(a)



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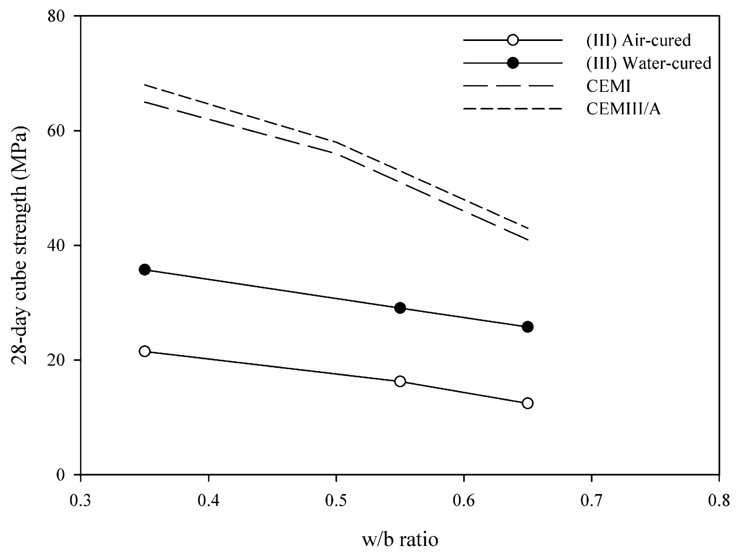

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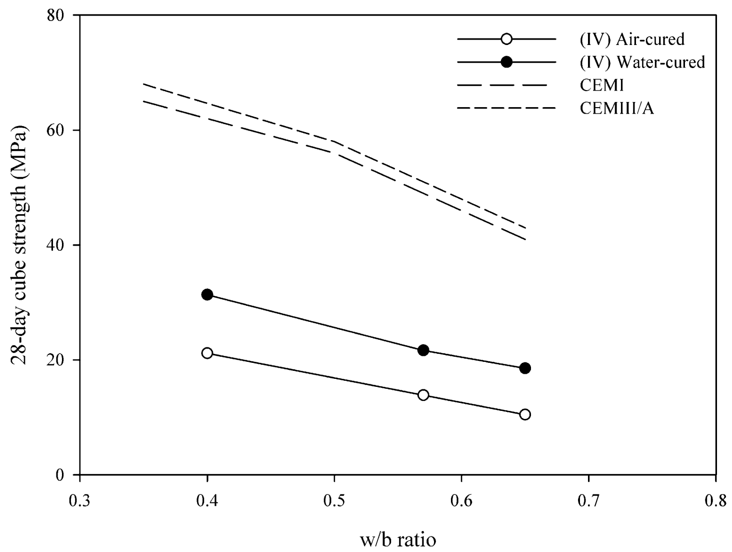


(d)

Figure 16: Relationship between w/b ratio and 28-day compressive strength

For fully compacted PC concretes compressive strength is has been shown to be inversely proportional to w/b ratio as defined by Abram's law [24]. Insufficient compaction at low w/b ratios typically prevents this idealised relationship in practice. The results plotted in Figure 16 suggest a similar relationship is true for lime-pozzolan concretes.

The parallel nature of air-cured and water-cured plots in each case suggest that the relationship between w/b ratio and compressive strength is largely unaffected by the curing conditions.

In the case of concrete (I) the markedly reduced cube strengths, attained by concretes prepared at a w/b ratio of 0.35, are likely to have been caused by poor compaction, leading to an increase of air voids and thus a reduction in compressive strength, at low w/b ratios. Poor compaction in this specific case is attributed to the particularly high cohesion and poor workability of the fresh paste. This in turn can be attributed to secondary forces arising from the physical nature of the metakaolin, which is made up of flat plate-like particles with a high-specific surface area (19,000m^2/kg). Although this is surface area is less than that of silica fume (22,000m^2/kg), the secondary forces acting between the adjacent plates are higher than those acting between the spherical particles of silica fume. An attempt to improve the rheology of fresh lime-pozzolan pastes using water reducing admixtures revealed that this concrete was unaffected by addition of a normal low dosage of superplasticiser. Results of this investigation are beyond the scope of this paper.

The relationship between the w/b ratio and strength of lime-pozzolan concretes demonstrates the potential for attaining 28-day compressive strengths in excess of 40 MPa by improving compaction at w/b ratios of 0.35. It is evident that a suitable superplasticiser must be identified to improve compaction of lime-pozzolan binders at lower w/b ratios allowing the production of higher strength concretes.

The compressive strengths observed in this study are significantly higher than those reported in earlier studies [11]. That said the results show that the strength development exhibited by the two PC-based reference concretes is substantially higher, particularly at early ages.

Compressive strengths in excess of 30 MPa at 28-days, attained by two of the four lime-pozzolan concretes, are thought to corroborate the technical feasibility of producing a structural strength concretes using hydraulic lime. Lime-pozzolan concretes (II) and (III), which incorporated 25% SF & 25% GGBS and 30% SF respectively, showed almost identical strength development at a w/b ratio of 0.65 and attained maximum cube strengths of 37 MPa and 34 MPa respectively at 56-days. By extrapolation of the relationship between w/b ratio and compressive strength, it seemed possible that lime-pozzolan concrete (II), incorporating 25% SF & 25% GGBS, might have attained a 28-day cube strength in excess of 40 MPa, had it been possible to produce a compactable fresh concrete at a w/b ratio of 0.35. On this assumption, lime-pozzolan concrete (II), was deemed to show the greatest potential, of the four concretes tested, for attaining higher strengths in future tests utilising superplasticisers. The compressive strength gain of lime-pozzolan concrete (I), which incorporated 15% FA & 15% MK, was considerably lower than the other three concretes suggesting that silica fume, or an alternative source of soluble silica, is a likely to be a key constituent in structural lime-pozzolan concretes.

The fact that strengths in excess of 30 MPa were only attained by water-cured lime-pozzolan concretes is however a limitation in the potential implementation of these concretes. It is evident that appropriate curing is essential to ensure that lime-pozzolan concretes attain their anticipated compressive strengths. The observed disparity between air- and water-cured compressive strengths suggests a considerable sensitivity to curing conditions, which must inform judicious site practise. This sensitivity is however not overly dissimilar from the sensitivity of blended PC concretes [25] & [26] which are routinely specified for in-situ concrete applications.

The results have highlighted that moist curing is particularly important when lime-pozzolan concretes contain a large proportion of highly reactive pozzolanic additions. This observed result is consistent with studies that have shown that PC concretes incorporating pozzolanic additions are more sensitive to the influence of curing conditions than those without [25], [26]. In the case of PC concretes a strong relationship between the total binder content and the sensitivity to curing conditions has also been shown [27]; the higher the total amount of cement the greater the sensitivity of the system. On this basis it is reasonable to anticipate that the sensitivity of future lime-pozzolan concretes might be reduced by limiting the overall binder content, which at 540kg/m^3 was notably high for specified concretes.

One might note that the water- and air-cured conditions that samples are subject to in the laboratory represent extreme cases and are not representative of curing onsite. In reality site cured concrete typically comprises larger elements subject to varying conditions, including surface effects such as localised wetting and drying. The importance of concrete sensitivity to curing conditions is thus highly dependent on the project application. Greater requirements for moist curing will not favour the adoption of lime-pozzolan concretes as it tends to increase project costs by lengthening construction programmes. The sensitivity of lime-pozzolan concretes to curing conditions is expected to be reduced by the use of suitable water reducing admixtures.

As with Portland-cement concrete, the relationship between w/b ratio and strength has a large impact on site practice, as the addition of mix water during placement has the potential to substantially reduce the concrete strength. The w/b ratio of the concrete is not only affected by the addition of mix water, but also by the moisture condition of the aggregate at the point of use. For example, care must be taken when saturated aggregates are used in the production of concrete, with alterations to the mix design often necessary to prevent the additional water in the mix having an adverse effect on the strength development of the material.

A further investigation into the effect of the curing regime on the strength development of lime-pozzolan concretes demonstrated that 14-days water-curing, followed by 14 days air curing, produced the highest 28-day compressive strengths. Neville (2011) similarly shows that increased compressive strengths can be achieved by moving PC concrete samples from water to air after 7, 14 or 28-days [28].

Compressive strengths observed in this investigation continue to challenge the broadly accepted view that lime-based building materials are notoriously weak and slow to set. Although only relatively moderate strength gains have been attained in this study, there is good evidence to suggest that considerable strength gains are achievable in lime-based concretes with the right combination of pozzolanic additions, right w/b ratio and curing regime.

Elastic modulus

The cylinder strength (f_{cyl}), elastic modulus (E_c), compressive strain at the maximum stress (ε_{c1}) and nominal ultimate strain (ε_{cu1}) for each of the four lime-pozzolan concretes are shown in Table 5.

Table 5: Elastic modulus and compressive strain of lime-pozzolan concretes

Composition	*w/b*	f_{cy1} MPa	E_c GPa	ε_{c1}	ε_{cu1}
70% NHL5, 15% FA & 15% MK (I)	*0.65*	18.4	7.0	0.003	0.003
	0.57	16.8	9.0	0.004	0.007
	0.35	22.1	21.0	0.004	0.004
50% NHL5, 25% SF & 25% GGBS (II)	*0.79*	19.2	7.0	0.005	0.006
	0.66	20.0	13.5	0.006	0.006
	0.55	28.1	12.5	0.004	0.006
70% NHL5 & 30% SF (III)	*0.65*	12.0	4.5	0.003	0.007
	0.55	19.4	8.5	0.005	0.005
	0.35	19.8	11.5	0.003	0.008
50% NHL5, 25% SF & 25% FA (IV)	*0.65*	15.1	14.0	0.004	0.006
	0.57	20.1	20.5	0.004	0.004
	0.40	22.3	14.0	0.003	0.003

The elastic modulus of these lime-pozzolan concretes was observed to vary between 7 and 21GPa. For concrete classes C12/15 > x ≤ C50/60 the elastic modulus normally varies between 27-37GPa [30] and the strain at failure between 0.001 and 0.005 [28]. In the case of the four lime-pozzolan concretes the compressive strain at the maximum stress (ε_{c1}) is observed to vary between 0.003 and 0.006. In Eurocode 2 the maximum compressive strain of concretes of different strength classes is provided; for concrete classes ≤ C50/60 the highest value of ε_{c1} assumed for ultimate limit state design is 0.0025 [30]. All the lime-pozzolan concretes tested attained a maximum compressive strain greater than 0.0029 before failure. The results show that the nominal ultimate strain (ε_{cu1}) of the lime-pozzolan concretes varies between 0.003 and 0.008, the nominal ultimate strain (ε_{cu1}) for concrete class ≤ C50/60 (EC2) is 0.0035 [31]. Based on these test results a reduced value of ε_{cu1} must therefore be assumed for design.

Figure 17 depicts the relationship between cylinder strength and elastic modulus of these lime-pozzolan concretes in comparison to two PC-based reference concretes, which are seen to correspond to the theoretical relationship defined in Eurocode 2 [30]. Consequently, from extrapolation of the results it could be suggested that lime-pozzolan concretes are less stiff than PC concretes of equivalent strength. The results are also compared with the empirical relationship between compressive strength and elastic modulus of PC concretes containing pozzolanic additions, over a range of densities, as proposed by Nassif et al. (2005) [32].

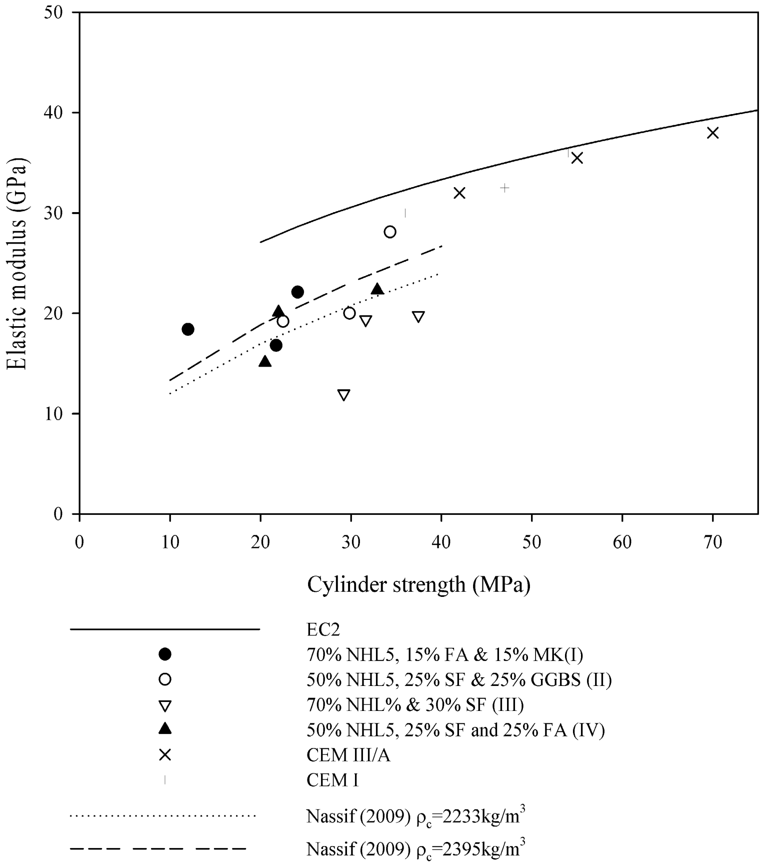


Figure 17: Relationship between elastic modulus and cylinder strength at 90 days

The results demonstrate that the modulus of elasticity-compressive strength equation in EC2 for PC-concretes, substantially over-estimates the elastic modulus (E_c) of lime-pozzolan concretes. Previous studies have shown that alumina-siliceous additions have an effect on the rate of increase and maximum elastic modulus of PC-based concretes [33] & [32]. Nassif et al. (2005) propose an empirical equation for high performance concrete containing pozzolanic additions:

$E_c = 0.036(\rho_c)^{1.5}\sqrt{f_{cyl}}$ (equation 1.1)

Where ρ_c = density (kg/m^3) and f_{cyl} = 28-day cylinder strength

Equation 1.1, which is plotted in Figure 17, is shown to be a reasonable predictor of the elastic modulus of three of the four lime-pozzolan concretes tested, which had densities ranging between 2233 kg/m^3 and 2395 kg/m^3. The lime-pozzolan concrete containing 30% SF had a lower elastic modulus and having an average density of 2256 kg/m^3 is best described by the equation, $E_c = 0.027(\rho_c)^{1.5}\sqrt{f_{cyl}}$.

The elastic modulus of concrete is not a determinate of structural performance at the ultimate limit state but rather the effective modulus ($E_{c,eff}$) is used to predict flexural cracking at the serviceability state [31]. The creep behaviour of lime-pozzolan concretes needs to be established before this reduced elastic modulus value can be deduced. With appropriate attention to serviceability criteria, the elastic modulus of lime-pozzolan concretes is unlikely to prevent their use in the majority of structural applications. Onerous structural applications will typically be precluded by compressive strength before elastic behaviour.

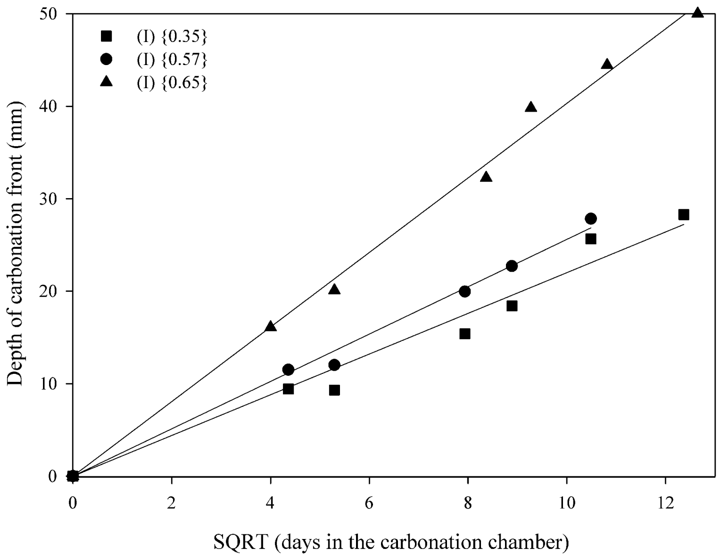
Carbonation resistance

A laboratory-based test was used to determine the rate at which the carbonation front moves through the material. The results give an indication of how many years the lime-pozzolan concrete will provide protection against carbonation-induced corrosion caused by de-passivation of steel reinforcing bars. The carbonation resistance of a concrete determines the minimum amount of cover required for design in order to protect the reinforcing steel from corrosion within the lifetime of the structure.

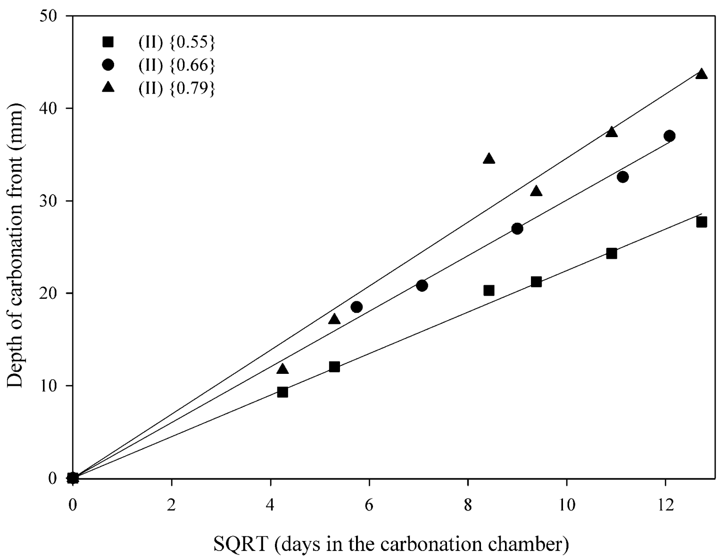
In the assessment of concrete structures the rate of carbonation, or the CO_2 penetration rate, is assumed to obey a square root law (see eq. 2.1) [39]. The constant K_c is a property of the material and a measure of the quality of the concrete.

$$\text{carbonation depth, } x = K_c.\ \sqrt{\text{time}} \qquad \text{(equation 2.1)}$$

Plotting the best-fit linear relationships between the average depth of the carbonation front and the square-root of the number of days in the accelerated carbonation chamber (Figure 18) clearly demonstrates that the same a square root law is valid in the behaviour of lime-pozzolan concrete.

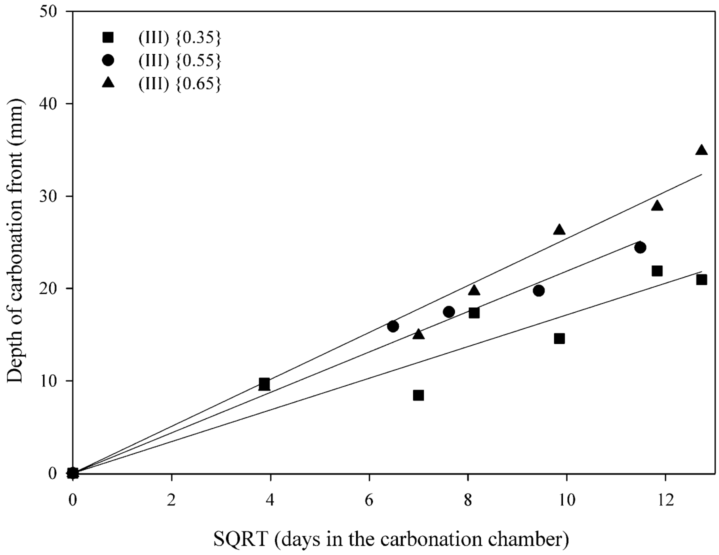


(a)



(b)

Figure 18: Measured carbonation resistance cont…



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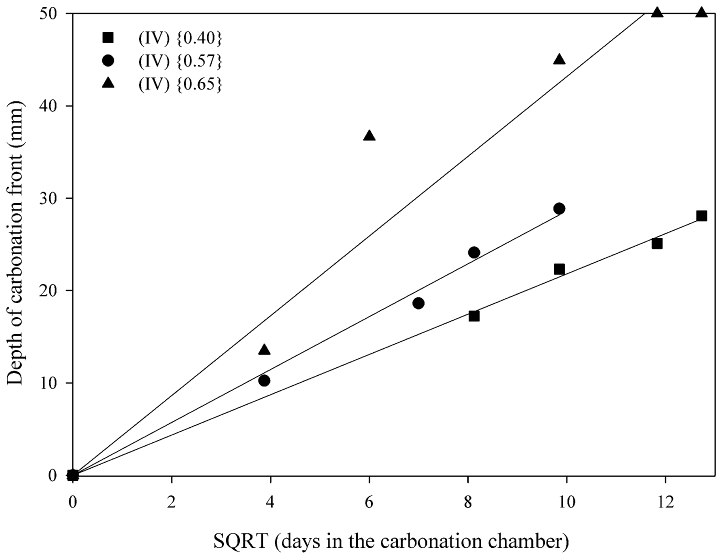


(d)

Figure 18: Measured carbonation resistance

The carbonation resistance of these lime-pozzolan concretes is lower than that of the Portland-cement based concretes investigated by Dhir et al. (2001) [37]. By extrapolation of tests results presented by Dhir (2001), a comparable PC concrete (with a carboniferous limestone aggregate and a water content of 240kg/m^3) at a w/b 0.65, might be expected to carbonate around 20mm in 20 weeks at 4% CO2 exposure (where 1 week ≈ 1 years natural exposure). The results in Figure 18 imply that these lime-pozzolan concretes, at a w/b ratio of

0.65, would carbonate between 30 and 60mm in the same period. This implies that lime-pozzolan concretes are less effective than PC concretes at protecting steel reinforcement from corrosion.

In each of four lime-pozzolan concretes it can be seen that an increase in w/b ratio increases the rate of carbonation. This is as expected, with an increased w/b ratio leading to an increased porosity and thus an easier passage of gaseous CO_2 through the hardened matrix [24]. Figure 19 shows the best-fit relationship between K_c and w/b ratio for the four lime-pozzolan concretes. The results evidence that the resistance of lime-pozzolan concretes to carbonation is proportional to the w/b ratio of the mix.

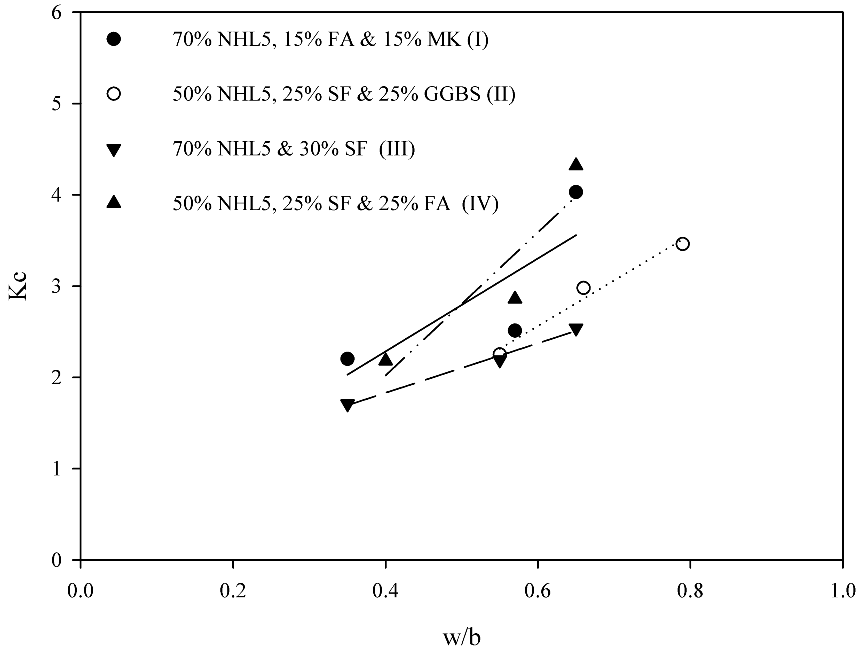


Figure 19: Relationship between w/b ratio and Kc

Not only does the inclusion of alumina-silicate additions affect the carbonation resistance of the concretes prepared at a given w/b ratio, but the varying gradients of the best-fit linear relationship between Kc and w/b ratio (shown in Figure 19) suggests a variation in the sensitivity of the four lime-pozzolan concretes to changes in w/b ratio. The carbonation resistance of the lime-pozzolan concrete prepared with 30% SF is least affected by the variation in w/b ratio at which it is prepared, whereas lime-pozzolan concrete prepared with 25% SF and 25% FA is observed to be the most sensitive. Given that carbonation resistance is highly dependent on the pore structure of the matrix, the sensitivity of the different lime-pozzolan concretes to changes in w/b will be affected by the morphology and adsorption characteristics of the alumino-silicates [40].

Table 6: Rate of carbonation

Composition	w/b	Kc	Years to carbonate 40 mm	Years to carbonate 50mm
70% NHL5, 15% FA & 15% MK (I)	*0.65*	3.6	18	28
	0.5	2.8	29	46
	0.35	2.0	56	87
50% NHL5, 25% SF & 25% GGBS (II)	*0.65*	2.8	29	45
	0.5	2.1	54	84
	0.35	1.3	133	207
70% NHL5 & 30% SF (III)	*0.65*	2.5	36	57
	0.5	2.1	52	81
	0.35	1.7	80	124
50% NHL5, 25% SF & 25% FA (IV)	*0.65*	4.0	14	23
	0.5	2.8	29	45
	0.35	1.6	86	135

Table 6 provides calculated K_c values for each of the lime-pozzolan concretes prepared at standard w/b ratios based on extrapolated results.

Although the carbonation resistance of lime-pozzolan concretes is low in comparison to PC concretes it can be suggested from the results that a lime-pozzolan concrete incorporating 25% SF & 25% GGBS may be able to provide sufficient protection for steel reinforcement for around 130 years. Increasing the depth of cover from 40 to 50mm increases this to over 200 years. A previous study looking at the carbonation resistance of blended PC concretes, has shown that a ternary binder incorporating both SF and GGBS is highly effective in producing a dense pore structure, which hampers the diffusion of CO_2 [38].

Extrapolation of the results suggests that, at a w/b ratio of 0.35, three of the four lime-pozzolan concretes, (II), (III) & (IV) could provide in excess of 60 years protection from 40mm cover. This observed result reinforces the need to identify a suitable water-reducing admixture to facilitate production of lime-pozzolan concretes at low w/b ratios.

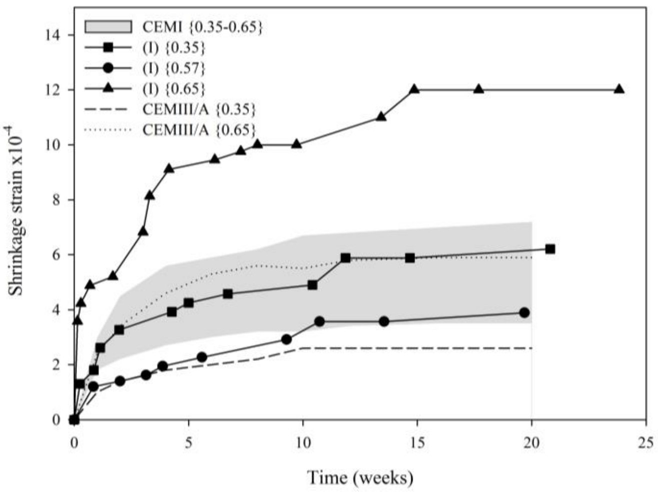
Although lime-pozzolan concretes have been shown to provide adequate carbonation-resistance to provide sufficient protection for carbon steel for the typical design life of a modern building, the durability of ancient lime-pozzolan concrete structures, raises a question about the appropriateness of this composite structural solution. If non-metallic reinforcement was used, negating the need for this corrosion protection, then the rate of carbonation might rather be conceptualised as the carbon-dioxide capture rate. In this scenario the higher rate of carbonation in lime-pozzolan concretes would be considered beneficial in sequesting atmospheric CO_2 and offsetting carbon emissions associated with the manufacture of the binder.

Alternative reinforcement options include both non-metallic reinforcement bars, such as glass or basalt fibre reinforced polymers [41] or bamboo [42] as well as Fibre Reinforced Concrete (FRC) solutions containing dispersed synthetic or natural fibres such as sisal, hemp and coir [43] & [44]. Stainless or galvanised steel reinforcement could feasibly be used in lime-pozzolan concretes, but the typical cost of these solutions would generally be prohibitive and their use likely to negate environmental benefits associated with specifying the lime-pozzolan concrete. Cathodic protection is another potential solution for carbon-steel reinforced lime-pozzolan concrete structures exposed to the environment.

Linear shrinkage

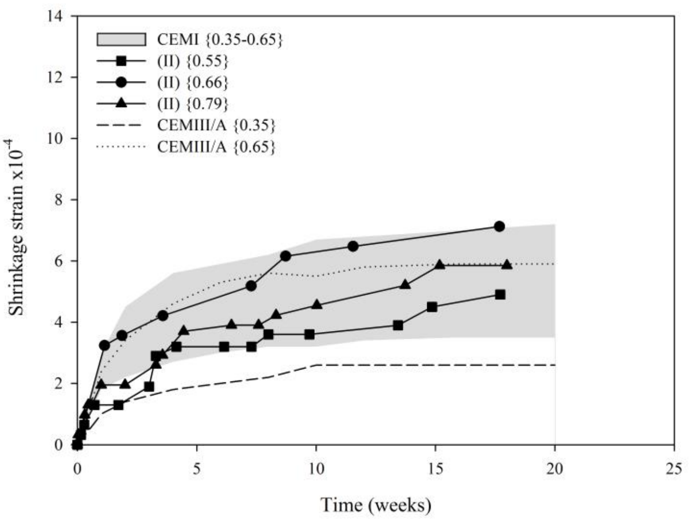
This test determines the rate and extent to which a sample of lime concrete will shrink during curing at standard conditions.

Figure 20 shows the change in the calculated shrinkage strain over time in comparison to equivalent measurements on reference CEM I and CEM III/A concretes.

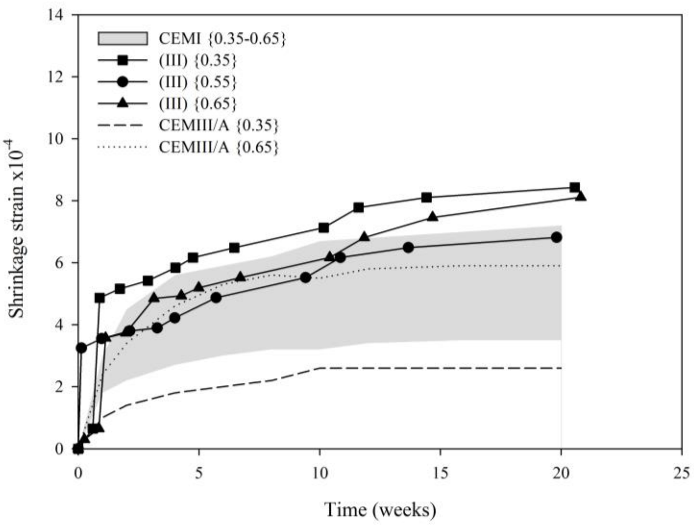


(a)

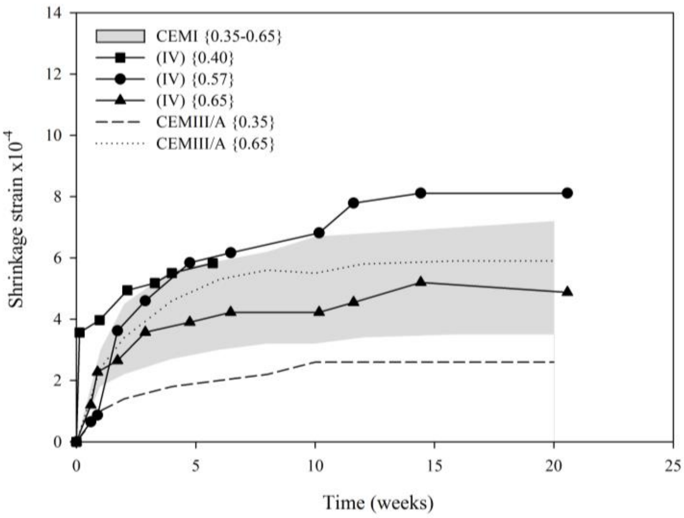
Figure 20: Linear shrinkage of lime-pozzolan concretes cont...


CEMI {0.35-0.65}
(II) {0.55}
(II) {0.66}
(II) {0.79}
CEMIII/A {0.35}
CEMIII/A {0.65}
Shrinkage strain x10^{-4}
Time (weeks)
0
2
4
6
8
10
12
14
0
5
10
15
20
25

(a)


CEMI {0.35-0.65}
(III) {0.35}
(III) {0.55}
(III) {0.65}
CEMIII/A {0.35}
CEMIII/A {0.65}
Shrinkage strain x10^{-4}
Time (weeks)
0
2
4
6
8
10
12
14
0
5
10
15
20
25

(b)



(c)

Figure 20: Linear shrinkage of lime-pozzolan concretes

Although the results show that the w/b ratio of the concrete clearly affects the total linear shrinkage of the specimen, no clear relationship between the two properties is seen in the results. Typically a higher w/b ratio would be expected to result in a higher shrinkage strain, due to the increased potential for volumetric changes resulting from the evaporation of the free water during drying. However for samples prepared at low w/b ratios, the measured shrinkage could have been affected by on-going autogenous shrinkage, which in the case of PC-concrete is assumed to have been completed in the initial period of water curing. It has previously been shown that SF has a substantial impact on the autogenous shrinkage of high-strength PC concretes, with 15% of SF increasing autogenous shrinkage by 50% [46]. A slower hydration reaction leading to longer-term self-desiccation in lime-pozzolan concretes could, for example, have resulted in the in concrete (III) exhibiting the maximum linear shrinkage at the minimum w/b ratio [0.35].

Figure 20 graph (b) clearly shows that the linear shrinkage of a lime-pozzolan concrete incorporating 25% SF and 25% GGBS is within the range of shrinkage measurements for the CEM I reference concrete [0.35-0.65] at all w/b ratios. The linear shrinkage of the lime-pozzolan containing 30% SF (III) was observed to be greater than that of the PC reference concretes but this was the concrete whose shrinkage was least affected by the variation of the w/b ratio at which it was prepared. In contrast lime-pozzolan concrete (I), the only concrete not containing any SF, displayed a very broad range of shrinkage strain values. Although the shrinkage of this lime-pozzolan concrete was comparable with the CEM I concrete at a w/b ratio of 0.35, the shrinkage strain was observed to be almost twice that of the CEM I concrete when compared at a w/b ratio of 0.65. These observed results not only highlight the considerable sensitivity of lime-pozzolan concrete (IV) to changes in w/b ratio but also make a case for the inclusion of SF for limiting the sensitivity of lime-pozzolan concretes to shrinkage in applications where this is important.

Comparing the results of the two reference concretes it is apparent that inclusion of 50% GGBS is effective in reducing the linear shrinkage of PC-based concretes. Similarly the least drying shrinkage, across all w/b ratios, was seen observed in lime-pozzolan concrete (II), incorporating 25% SF and 25% GGBS.

The importance of limiting the ultimate drying-shrinkage of concretes is highly dependent on their application in use. It is the restraint provided by support conditions, or friction at the interface of discrete materials, which tends to constrain deformation and induce cracking or warping of concrete elements during drying. Limiting drying shrinkage is particularly crucial in the case of ground floor slabs where drying shrinkage can lead to curling of slabs as well as detrimental cracking. In many applications it is important to know the maximum shrinkage strain for design, for example in the case of pre-stressed concrete, where drying shrinkage acts to reduce pre-stressing forces.

The observed drying shrinkage of the tested lime-pozzolan concrete specimens was, in the vast majority of cases, broadly in line with that of the PC-based control concretes over a 20 week period. The ultimate strains of all the concretes tested, including the controls, were shown to be slightly higher than the ultimate strain of 560 microstrain, calculated, in accordance with CIRIA Guide C660 [47], for an equivalent Class N Portland-cement concrete stored at 20°C and 60-65%.

Given the shrinkage strain plot for the lime-pozzolan concretes does not clearly plateau within the first 20-weeks of testing, it is clear that drying shrinkage needs to be monitored over a longer period before an ultimate shrinkage strain can be defined for design purposes. In practise incorrect detailing of lime-pozzolan concretes could lead to cracking or deformation over a longer period. However provided that the ultimate shrinkage strain is not found to be substantially higher than the 20-week results imply, it would be feasible to accommodate this degree of drying shrinkage in design.

That said, the results also suggest that there are opportunities to minimise the drying shrinkage of lime-pozzolan concretes through the selection and combination of alumino-siliceous additions. The results suggest for example that silica fume is effective in minimising the sensitivity of lime-pozzolan concretes to variations in w/b ratio. This is clearly beneficial in practise as it mitigates the risk of high w/b ratios leading to excessive shrinkage. The results of the control samples also suggest that the incorporation of 50% GGBS is effective in reducing the linear shrinkage of PC-concretes. Similarly the high proportion of GGBS in concrete (II) could have been responsible for limiting shrinkage in comparison to concrete (III). The sensitivity of concrete (I) to changes in w/b ratio raises concerns about the suitability of this ternary combination of additions.

Conclusions

The purpose of this investigation was to ascertain the technical feasibility of producing a structural strength concrete using hydraulic lime as an alternative cementitious binder to Portland cement. The results reported in this paper uphold the technical feasibility of a structural strength lime-pozzolan concrete. Similarities in the mechanical behaviour and performance of lime-pozzolan and Portland-cement concretes engender confidence in the technology, whilst differences provide opportunities for developing lime-pozzolan concretes with beneficial properties which would differentiate this future material from the current technology.

It is evident that the production of lime-pozzolan concretes at low w/b ratios results in the strongest and most durable concretes. Having been unable to produce and compact lime-pozzolan concretes at low w/b ratios it is clear that a suitable water-reducing admixture needs to be identified.

Looking across the results of this suite of tests, one combination of additions stands out as having outperformed the other three combinations. Concrete (II), which incorporated 25% SF and 25% GGBS, exhibited the greatest initial and long term strength gain, the highest strain at the maximum compressive strength (ε_{c1}), the greatest carbonation resistance and the least drying shrinkage.

The results imply that silica fume, or an alternative source of soluble silica such as rice husk ash [48], will be a key constituent of future lime-pozzolan concretes. Given that the dosage of SF in PC concretes is currently limited to a maximum of 10% [49] for both mechanical performance and for commercial viability, it is acknowledged that the high dosage of silica fume used in this study may be untenable in future lime-pozzolan concretes. In recognition of commercial and legislative constraints it is recommended that future studies using SF limit its use to 10% of the total binder.

Although this study has demonstrated unprecedented compressive strengths for lime-based concretes it is important to recognise that these initial lime-pozzolan concretes have exhibited only moderate strengths and tolerable durability in comparison with the reference PC-concretes. With the global cement industry exploiting considerable economies of scale in the supply of low cost PC into the market, it seems that only superior performance, in conjunction with reduced environmental impact, will see new low carbon cements becoming a viable alternative. High levels of deterioration in steel reinforced concrete structures, and associated remediation or replacement costs, have created opportunities for innovative concrete solutions, which can both prove both their durability and life-cycle cost effectiveness.

Moreover, superior performance need not necessarily demand greater mechanical strengths. Rather enhanced performance might be manifested in improved compatibility with other construction materials, or systems, or differential properties such breathability, flexibility or the absorption of carbon dioxide. As new low carbon cements are being developed it would seem timely to revaluate our utilisation of PC-concrete. With no single cementitious binder promising to match the wide scale availability and universal applicability of Portland-cement, we might be headed towards a diversification of the concrete market, with a palette of new low carbon binders appropriate to specific applications and geographical locations. This ‘engineered’ concrete model underpins high-performance concrete (HPC) technology [44], although this terminology increasing tends to refer to particularly high-strength concretes.

This discussion about the required properties and performance of concretes in different applications is important as it has the potential to propel and steer the low carbon concrete research agenda. The relatively fast rate of carbonation observed in this study of lime-pozzolan concretes is a good example. If passivation of carbon steel is a critical requirement of this new concrete technology then it might be appropriate to terminate this line of inquiry, on the basis of the observed results, even at this early stage. However if non-metallic reinforcement bars or fibres are to be increasingly utilised, removing this particular durability requirement, then the increased rate at which this material absorbs atmospheric CO_2 might be deemed beneficial.

The feasibility of producing a structural strength lime-pozzolan-concrete has been demonstrated. It is expected that identification of a suitable water-reducing admixture could provide further improvements in compressive strength and durability. Subsequent testing will focus on the development of a ternary blend of NHL5, SF and GGBS, which of the four lime-pozzolan concretes tested showed the best potential for a high-strength structural grade lime-pozzolan concrete. In the light of these results, additional structural characteristics that will be of interest in the development of lime-pozzolan concrete include tensile strength and creep.

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8.3 PAPER 3: Lime-pozzolan concretes: addressing project-specific questions

E R Grist[a,b], K A Paine[b], A Heath[b], J Norman[c], H Pinder[a]
a. Ramboll, 40 Queen Square, Bristol, BS1 4QP, UK
b. University of Bath, Claverton Down, Bath, BA2 7AY, UK
c. University of Bristol, Bristol, BS8 1TR, UK

Abstract

This study was undertaken to develop a novel lime-pozzolan concrete appropriate for a 'real-world' structural application. The paper describes a sequence of laboratory tests undertaken to explore and enhance the material performance of ternary combinations of hydraulic lime, ground granulated blastfurnace slag and silica fume.

The research demonstrated the feasibility of producing lime-pozzolan concretes with 28-day strengths in excess of 45MPa suitable for reinforced structural members. Specific aspects of material performance considered in this paper are workability, binder composition, cold-weather curing and the flexural behaviour of reinforced lime-pozzolan concrete beams.

Keywords: lime-pozzolan concrete, workability, compressive strength, elastic modulus, flexural strength

Introduction

Research into this low-CO_2 concrete technology was initiated by an architect who inquired about the technical feasibility of constructing a doubly-curved 'limecrete' shell roof for an innovative eco-house. With no modern precedence for the use of lime in the production of structural components and little or no data, academic or otherwise, to offer an answer, a laboratory investigation was designed to investigate the feasibility of this concept. The results of initial material testing, which is reported elsewhere [1] & [2], demonstrated that mechanical strengths comparable to other cementitious materials could be attained in the laboratory.

It was however recognised that a small number of test results, based on lab-cured specimens, can do little to address issues of viability in practice, including: consistence (workability), site-curing, appearance and structural design. The experimental programme reported in this paper was undertaken to address a number of specific issues arising from the potential implementation of this novel technology in the field. These issues were either identified from previous experience in the laboratory or anticipated from 'real-world' application.

The starting point in developing a lime-pozzolan concrete mix design suitable for implementation was to overcome a problem encountered in earlier testing. It had previously been shown that production of lime-pozzolan concretes at low w/b ratios resulted in the strongest and most durable concretes [2], however these mixes had been very difficult to compact.

The origin of the name 'lime', stems from it being a 'sticky' or 'slimy' material [3]. Whereas ancient lime-pozzolan concrete, known as *opus caementicium,* was tamped against wooden shuttering, modern construction practice favours mechanisation over workmanship and today concrete is a fluid material capable of being poured or pumped into formwork around a complex network of reinforcement. For casting modern lime-pozzolan concretes in-situ, a slump of 100 to 150mm (slump class S3) will typically be required to facilitate pouring and compaction on site [4]. Historically organic substances, such as egg white, blood, casein, beer, vegetable juices, tannin and urine were used to improve the workability of fresh concrete [5], but today the concrete industry relies on the performance of synthetic water-reducing admixtures (WRAs) such as superplasticisers. If this 'traditional' material was to be used in modern applications, it was clear that a suitable WRA needed to be identified to improve the consistence of the fresh mix and negate the need for onerous manual compaction. Figure 21 photographs (a) and (b) depicts fresh lime-pozzolan concrete before and after addition of superplasticiser respectively.

(a) **(b)**

Figure 21: Fresh lime pozzolan concrete before and after SP addition

Material and methods

The experimental programme was split into four distinct studies:

i. Study 1 was carried out to improve the rheology of fresh lime-pozzolan concretes and to understand the relative effectiveness of a range of superplasticising admixtures and how they influenced compressive strength development.
ii. The most promising superplasticisers were then utilised in study 2, which aimed to enhance the compressive strength of the lime-pozzolan concrete, by modifying the composition of the ternary lime-pozzolan binder, specifically altering the ratio of NHL5 to GGBS.
iii. Study 3 considered the influence of cold weather curing on the compressive strength development of lime-pozzolan concretes. The strength development of specimens cured in winter weather conditions was compared with those cured in controlled laboratory conditions.
iv. Building on the findings of the previous studies, study 4 investigated the flexural behaviour of two reinforced lime-pozzolan concrete beams.

The hydraulic limes used throughout the programme were NHL5, NHL3.5, NHL2 conforming to [6], all of which were sourced from a single manufacturer and supplied by a specialist lime-building merchant in the UK. The silica fume (SF) was obtained in the form of a slurry, with a SF:water ratio of 50:50 by mass, and conformed to BS EN 13263 [7]. The ground granulated blastfurnace slag (GGBS) conformed to BS EN 15167 [8]. Chemical and physical data on these five constituent materials, as provided by their respective suppliers, is given in Table 7.

Table 7: Chemical composition of constituent minerals

	NHL5	NHL3.5	NHL2	SF	GGBS
Oxide analysis (% by weight)					
SiO_2	15.0	12.0	6.0	94.5	35.1
Al_2O_3	1.9	1.7	1.3	0.3	14.0
$K_2O + Na_2O$	0.3	0.2	0.2	1.3	0.0
Fe_2O_3	0.6	0.5	0.4	0.3	0.4
TiO_2	0.2	0.2	0.1	0.0	0.7
CaO	59.0	56.0	63.0	0.3	39.9
MgO	1.0	1.0	0.8	0.5	9.0
MnO	0.0	0.0	0.0	0.0	0.4
Particle density (kg/m^3)	2,670	2,670	2,670	2,200	2,890
Surface area (m^2/kg)	800	900	1,100	22,000	2,650

The coarse aggregate was a 5-10mm and 10-20mm crushed carboniferous limestone. The fine aggregate comprised 50% Marlborough grit and 50% alluvial sand by weight. The particle size distribution (PSD) of each aggregate was determined in accordance with BS 933-1:2012 [9] and is shown in Table 8.

Table 8: PSD of the aggregates

	% passing			
Seive size (mm)	Coarse aggregate	Fine aggregate	Marlborough grit	Alluvial sand
40	100	100	100	100
28	100	100	93	100
20	87	100	54	99
14	25	100	38	96
10	1	87	17	93
6.3	0	22	0	82
4	0	0	0	10
2	0	0	0	1
1	0	0	0	0

The aggregates were assumed to have an absorption coefficient of 0.6% and were dried under ambient conditions in the laboratory for at least 24 hours prior to use to ensure they were consistently in a lab-dry state.

Study 1: Improving the rheology of fresh lime-pozzolan concretes

A preliminary trial confirmed that two proprietary SPs, developed for Portland-cement (PC) based concretes, could be employed to improve the properties of fresh lime-pozzolan concretes [10]. Further research was then conducted to investigate the influence of SPs on the flow and compressive strength development of lime-pozzolan binders, containing different aluminosilicate additions. Four proprietary SPs (designated G1, G2, G3 and G4) were identified for this study in conjunction with the admixture supplier. Details of the four SPs, as well as G5 that was used later on in this study, are reported in Table 9. The dosage range reported in Table 9 is the percentage recommended by the manufacturer for addition to PC-based concrete.

Table 9: Superplasticiser details

Reference	Specifc gravity	pH-value	Dosage
	g/cm^3		*(% weight of binder)*
G1	1.13 ± 0.03	5.5 ± 1	0.2-1.5
G2	1.13 ± 0.03	5.5 ± 1	0.2-1.5
G3	1.095 ± 0.02	6.5 ± 1	0.2-1.0
G4	1.06 ± 0.02	6.5 ± 1	0.3-1.2
G5	1.07 ± 0.02	7.0 ± 1	0.2-2.7

The superplasticisers in Table 9 are all polycarboxylic ether (PCE) polymers of the ‘Glenium’ family. G1 and G3 are based on third-generation PCE polymers and were developed for the ready-mix concrete industry. Third-generation PCE polymers primarily work by steric hindrance as opposed to the electrostatic dispersion of former generations. G2 is also a PCE polymer but includes a lignosulphonate-based water reducer. G4 was an early fourth-generation PCE being developed for the precast industry, which included a viscosity modifier. Finally G5 was also a fourth-generation PCE polymer tailored for the precast concrete industry.

In this empirical investigation the dosage of superplasticiser required to obtain a mortar with a flow-table diameter of 120+/-10mm, in accordance with BS EN 1015-3 [11], was used to assess the dispersing effectiveness of the PCE superplasticisers. A flow of 120+/-10mm was deemed to be desirable for production of the mortar bars, which were subsequently tested in compression in order to investigate the impact of the SP on the compressive strength of the hardened mortars. The use of mortar bars instead of concretes both minimised material usage and allowed easier comparison of binders as the coarse aggregate was not varied. The effect of lime ‘hydraulicity’ on the compressive strength development of the resulting lime-pozzolan mortars was also assessed by using all three hydraulic limes (NHL5, NHL3.5 and NHL2).

The mortars were prepared in a paddle mixer in the ratio 2 parts binder : 3 parts sand : 1 part water; (450g binder, 1350g sand, 225g water), in accordance with BS EN-196-1 [12]. Each mortar was incrementally dosed with a known mass of SP. After every incremental addition of SP the mortar was mixed for an additional 30 seconds to ensure thorough distribution. To minimise the impact of temporal effects, namely any variation in the slump retention characteristics of the four SPs, the precise flow diameter of each mortar was only measured once - immediately before casting.

To investigate the impact of the SP on the compressive strength development of the resulting hardened mortars, each mortar was prepared, cured and tested in accordance with BS EN 196-1 [12].

Study 2: Enhancing the composition of the ternary lime-pozzolan binder

Having identified the most promising SPs in Study 1, one SP (G3) was then adopted for the second study, which aimed to enhance the composition of the ternary lime-pozzolan binder. Scope for varying the dosage of SF in the ternary binder was limited by commercial and legislative constraints [2], so the effect of varying the ratio of GGBS to NHL5 was investigated.

A preliminary test was undertaken to investigate the effect of varying the ratio of hydraulic lime to GGBS. Two ternary NHL3.5-pozzolan mortars were tested, each dosed with 1.2% G3 (by mass of binder).

- 80% NHL 3.5, 10% GGBS & 10% SF [G3]
- 50% NHL 3.5, 40% GGBS & 10% SF [G3]

The mortars were prepared, cured and tested in accordance with BS EN 196-1 [12].

It became clear from the results of this preliminary trial that although lime-hydraulicity had a bearing on the compressive strength development of the lime mortars, that the inclusion of SP and the adjustment of the relative proportions of alumina-siliceous additions, had by far the most substantial impact on mechanical strength. Based on the findings further research was undertaken to investigate the influence of the ratio of GGBS to NHL5 on the strength development of lime-pozzolan concretes.

Four specific lime-pozzolan concrete mixes were produced and tested.

- 68% NHL5, 20% GGBS, 12%SF {w/b =0.42}
- 50% NHL5, 40% GGBS, 10%SF {w/b = 0.35}
- 60% NHL5, 30% GGBS, 11%SF {w/b =0.37}
- 56% NHL5, 34% GGBS, 10%SF {w/b =0.35}

The concretes were dosed with (1.2 ± 0.2%) superplasticer (G5) to produce lime-pozzolan concretes of equal consistence. The mix constituents are outlined in Table 10.

Table 10: Lime to GGBS ratio mix constituents of lime-pozzolan concretes

Mix description	Free water content	NHL5	GGBS	SF	Total binder	Fine sand	Marlborough grit	5-10mm	10-20mm	w/b
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	kg/m^3	
68% NHL5, 20% GGBS, 12% SF (I)	190	304	91	55	450	415	415	295	590	*0.42*
50% NHL5, 40% GGBS, 10% SF (II)	190	273	218	55	546	370	370	295	590	*0.35*
60% NHL5, 30% GGBS, 11% SF (III)	190	304	152	55	511	393	393	295	590	*0.37*
56% NHL5, 34% GGBS, 10% SF (IV)	190	304	182	55	541	373	373	295	590	*0.35*

The lime-pozzolan concretes were prepared in a rotary pan mixer according to the procedure detailed in BS 1881-125:1986 [14]. For each mix eight 100mm^3 cubes and one 150mm long, 300mm diameter cylinder was cast and cured in accordance with BS EN 12390-2:2009 [15]. The samples were cured under polythene sheeting for 24-hours before demoulding, upon which they were transferred to a conditioning lab, maintained at 20±0.5°C and 60-65% RH, until testing.

Compressive strength was measured in accordance with BS EN 12390-3:2002 [16] at 7, 28, 56 and 90 days. The cylinder strength (f_{cyl}), elastic modulus (E_c), compressive strain at the maximum stress (ε_{c1}) and ultimate strain (ε_{cu1}) of each concrete was also determined in accordance with BS EN 1881-121:1983 [17].

Study 3: The influence of cold-weather curing on compressive strength

Cold-weather curing is commonly held to be a severe problem for lime-concretes [18]. Public concern in the UK has been fuelled by a popular television programme, in which cold weather was seen to severely inhibit the set of a ‘lime-concrete’ floor slab [19]. It was recognised that it was necessary to be able to quantify the effect of ‘cold-weather curing’ on the strength development of these lime-pozzolan concretes to pre-empt industry concern. Rather than curing the material in controlled laboratory conditions, it was decided to investigate the strength development of lime-pozzolan concrete cubes subject to authentic cold-weather curing conditions.

For each of the four mixes (detailed in section 2.2) two additional $100mm^3$ cubes were cast. After 24-hours, upon de-moulding, these cubes were put inside hessian sacks and placed outside of the laboratory, where they were exposed to variable cold-weather conditions until testing. The mean daily temperature varied between 8°C and -7°C during the curing period. The cube strength of these cold-cured specimens was measured in accordance with BS EN 12390-3:2002 [16] at 28 and 56 days and compared with cube strengths of identical cubes cured in the conditioning lab maintained at 20±0.5°C and 60-65% RH.

Study 4: Flexural behaviour of reinforced lime-pozzolan concrete beams

The fourth study sought to address two fundamental questions that remained outstanding. Firstly, could a lime-pozzolan concrete be cast into structural elements with an appearance and surface finish similar to Portland cement concrete? And secondly, could such hydraulic lime-concrete elements be designed to Eurocode 2 (EC2)?

To address questions about the structural behaviour of reinforced lime-pozzolan concrete elements two 3 metre long reinforced lime-pozzolan concrete beams were tested in three-point bending. In order to assess the accuracy of EC2 [20] in modelling the behaviour of lime-pozzolan concrete structural components, the theoretical capacity of the two beams was calculated and compared with the empirical results. Two similar PC-concrete beams were also tested as control beams, against which the flexural behaviour of the lime-pozzolan concrete beams was compared.

The lime-pozzolan binder was 63% NHL5, 25% GGBS and 11% SF, the specific mix details are outlined in Table 11 alongside details of the PC control beams.

Table 11: Lime-pozzolan- and Portland-cement- concrete mix constituents

Constituent	LP beams (kg/m^3)	PC beams (kg/m^3)
PC	-	435
NHL5	304	-
GGBS	122	-
SF	55	-
Coarse aggregate	885	935
Marlborough grit	400	700
Building sand	400	70
Water	190	200
Superplariciser	5.8	-

The concretes were batched in a rotary pan mixer according to the standard procedure detailed in BS 1881-125:1986 [14]. One batch was required per beam. The lime-pozzolan concrete was dosed with 1.2% G5, which produced a mix with a slump of 170mm, determined in accordance with BS EN 12350-2: 2009. The PC concrete was produced at a w/b ratio of 0.46 and attained a similar slump without any superplasticisers.

The beams were cast in 230x120x3000 mm steel forms with the steel reinforcing bars laid on 25mm plastic spacers. Two alternative reinforcement layouts were prepared and tested for each concrete, denoted beam Type A and beam Type B. Type A and Type B beams were under- and over-reinforced for flexural failure respectively. Types A beams were reinforced with two H12 bars and Type B beams with four H12 bars (two pairs fixed one above the other) as outlined in Table 12. There were no shear links in any of the beams.

Table 12: Reinforcement details for the concrete beams

Beam Type	Cover to underside of beam (mm)	No. and size of longitudinal bars (mm)	Percentage of longitudinal reinforcement
A	25	2 x 12	0.8%
B	25	4 x 12	1.6%

The concrete was placed by hand in two layers, each of which was compacted with a vibrating poker. The top surface of each beam was finished by-hand with a float. Lifting eyes were cast into each beam to facilitate lifting into position for testing. The two lime-pozzolan concrete beams were cured at ambient conditions in the laboratory, under polythene sheeting, for a three week period before the formwork was struck. When the formwork was removed the beams were re-covered with polythene until one day before testing, when the beams were painted white. At this stage some hairline cracking was identified in the top surface of the Type A lime-pozzolan concrete beam. This was thought likely to have been caused during manoeuvring of the beam on a forklift.

For each batch of lime-pozzolan concrete eight $100mm^3$ cubes were cast for monitoring the compressive strength development of the mix, as well as a single 100x100x500 prism for measuring the 28-day flexural strength of the lime-pozzolan concrete. These prisms were demoulded after 24-hours and then cured in a conditioning lab maintained at 20±0.5°C and 60-65% RH. The compressive strength of these cubes was measured in accordance with BS EN 12390-3:2002 [16] at 28, 56, 90 and 180 days. At 28-days, the flexural strength of the lime-pozzolan concrete was also determined by centre-point loading in accordance with BS EN 12390-5:2009: Appendix A [21]. The applied loading rate (R) was determined to be $111N/mm^2$ based on a lower roller spacing of 300mm.

The beams were tested with one end pinned and the other on a roller support to allow horizontal movement. The load was applied using a 300kN hydraulic jack. Three transducers were used to monitor vertical displacements at the centre and quarter-points of the beams, the data being logged by a Measurement Group System 5000 Data Logger. The load was applied in 5kN increments, returning to zero after each new addition of load. All the beams were tested after 28-days, by which point the lime-pozzolan and PC-concretes had attained cube strengths of approximately 40MPa and 35MPa respectively.

Results and discussion

Study 1: The rheology of fresh lime-pozzolan concretes

The effect of four SPs on the consistence of the fresh lime-pozzolan mortars is shown in Table 13.

The sensitivity of the system to small changes in SP dosage (<0.2%) resulted in some mortars being cast outside of the desired range. Those mortars in which this was the case have been indicated in Table 13.

Composition	SP	Initial dosage	Final dosage	Flow Diameter (mm)
100 % NHL 2	G1	2.1%	5.0%	111
	G2	2.1%	> 5.0%	108
	G3	1.0%	<< 2.3%	139
	G4	1.0%	1.4%	127
100% NHL 3.5	G1	2.1%	2.5%	116
	G2	2.1%	3.0%	113
	G3	1.0%	< 1.2%	134
	G4	1.0%	1.3%	125
100% NHL 5	G1	1.6%	2.1%	118
	G2	2.1%	2.2%	117
	G3	2.1%	<<<* 2.1%	230
	G4	1.0%	<<<* 1.0%	217
90% NHL 3.5 & 10% SF	G1	2.1%	2.4%	121
	G2	2.1%	2.5%	113
	G3	1.0%	1.2%	128
	G4	1.0%	<<< 1.2%	143

Table 13: Lime-pozzolan mortar consistence

Considering the flow diameters of the fresh lime-pozzolan mortars shown in Table 13, it can be see that the effectiveness of the four SPs varied for each binder. For example it was observed that almost twice the dosage of G1 and G2 was required to achieve mortars of the same flow as those prepared with G3 and G4. In all four cases G2 was observed to be the least effective SP, requiring the highest dosage to achieve the same flow. The fourth-generation G4 product, which contained a viscosity modifier, was found to be the most effective.

The variation in mortar flow diameters reported in Table 13 also shows that the required dosage of SP is affected by the hydraulicity of the lime. Considering the three hydraulic-lime mortars prepared with G1, it is observed that the greater the hydraulicity of the lime, the less SP was required to achieve the same consistence. In workable mortars, good flow characteristics are realised when the surface of the particles are covered effectively with SP [22]. It therefore follows that the required dosage of SP is a function of the surface area of the particles. From Table 7 it can be seen that NHL2 has the highest surface area (1,100m^2/kg) and that NHL5 has the lowest surface area (800 m^2/kg). The total dosage required in the case of each of the lime-pozzolan mortars was substantially greater than the 0.2-1.5% recommended by the manufacturer for Portland-cement systems, consistent with the substantially lower surface area of PC (approximately 350 m^2/kg) [23]. Plotting the best-fit relationship between the required SP dosage and surface area of the binder (Figure 22) suggests a linear variation.

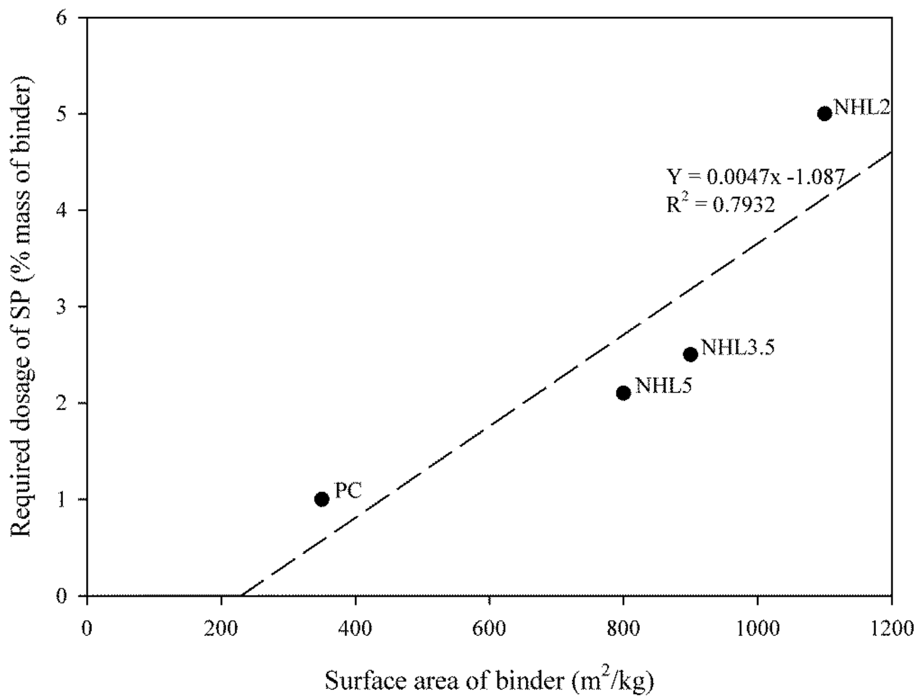


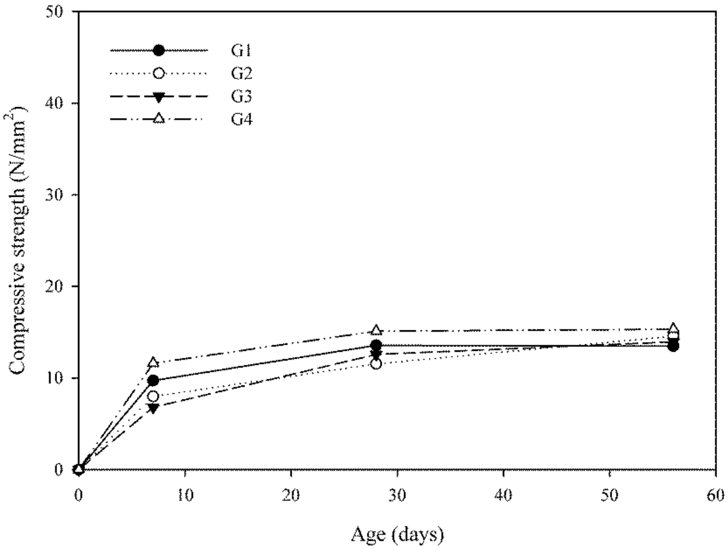
Figure 22: Relationship between required dosage of SP (G1) and surface area

Comparing the dosage of SP required in NHL3.5 mortars prepared with and without SF, it can be seen that the addition of 10 % SF typically reduced the demand for SP. This is the opposite of what has been observed in PC systems where the inclusion of SF has been observed to increase the required dosage of PCE [24] & [25], which Hommer (2009) suggested is the result of flocculation caused by PCE polymer bridging [25]. Given that addition of 10% SF approximately triples the total surface area of the lime binder, the results imply that the workability of the mix may then have been governed by the effective dispersion of the SF [22], perhaps indicating preferential absorption of the PCE on the SF than on the lime. The affinity of different particles for absorption of PCE is a function of both physical (specific surface) and chemical (surface charge) surface characteristics [24].

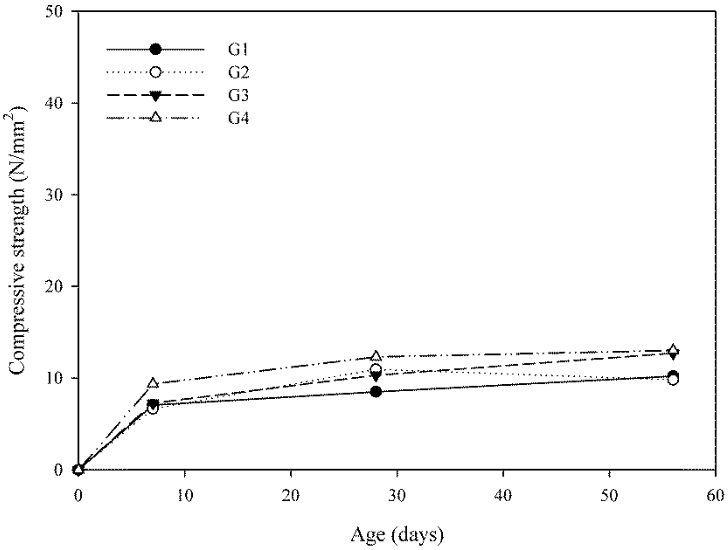
Results of this study raise questions about the structural and electrostatic compatibility of the PCE molecules, (comb polymers comprising a negatively charged anionic backbone and un-charged side chains of varying lengths and densities), with the ions on the mineral surface of the lime and SF particles [22]. Plank et al. has investigated the interaction between SF and a number of PCE superplasticers and has shown that in an alkaline environment, such as would be created in a lime-SF combination, that SF particles have a negative zeta potential (electrical potential at the solid-liquid interface) [26] due to deprotonation of the silanol groups on the surface of the SF [27]. However, in pore solution rich in Ca^{2+} cations, the surface charge can change from negative to positive as a result of electrostatic attraction of counter ions which can be adsorbed around the surface in an electrostatic double layer [28], [26]. If this occurred in the lime-SF solution then the SF could compete with the positively charged lime particles, for the absorption of the negatively charged backbone of the PCE polymer. Certainly the absorption mechanism between PCE and SF could be fundamentally different in lime and cement-based systems, as the zeta-potential of silica can be either positive or negative depending on the nature and concentration of salts in aqueous solution [29]. Specific modelling of the zeta potential of the constituent minerals in aqueous solution, with and without PCE, is needed to understand the absorption mechanism in binary and ternary lime-pozzolan binders.

The relative effectiveness of different PCE superplasticisers has previously been investigated for ultra high performance concretes (UHPCs) containing SF, which are commonly employed for refractory castables. Plank (2009) has found that methacrylate-based PCEs are more effective at dispersing cement particles and allylether-based PCEs are more effective at dispersing SF particles [22]. On this basis Plank recommends a blended PCE superplasticiser for binary cement-SF systems. Similarly a blended PCE superplasticiser might in future be specifically designed for binary or ternary lime-pozzolan binders, which would minimise the overall required dosage and thus also the embodied impact of the resulting lime-pozzolan concrete.

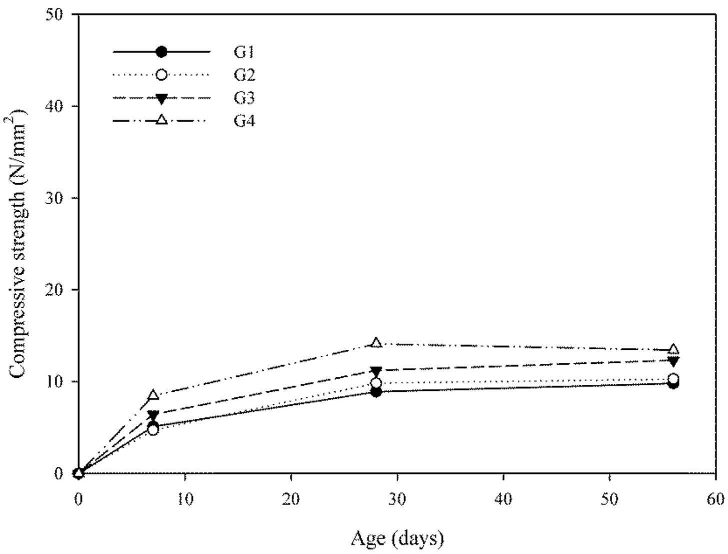
The effect of the four SPs on the compressive strength development of the hardened lime-pozzolan mortars is shown in Figure 23 graphs (a)-(d).



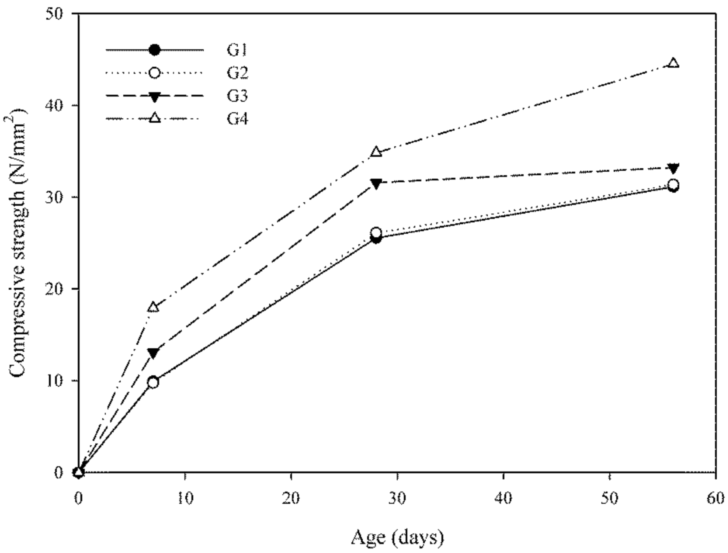
NHL5 (a)



NHL3.5 (b)



NHL2 (c)



NHL3.5-SF (d)

Figure 23: Compressive strength development of hydraulic lime mortars with similar flow characteristics controlled using four alternative SPs

The compressive strength development of the mortars illustrated in Figure 23 shows that the choice of SP has the greatest impact on the strength gain in the first 7-days. In the majority of the mortars the strength gain between 28 and 56 days is observed to be largely unaffected by the choice of SP.

There is no identifiable trend in the data that orders the four superplasticisers in terms of contribution to compressive strength in every case. However it is observed in all four of the hydraulic lime mortars that G3 and G4 resulted in the highest 56-day strengths. Specifically the use of G4 resulted in the highest strength lime-pozzolan mortars. This fourth-generation product contained a synthetic co-polymer which was designed to accelerate the early age strength development of PC-concrete by facilitating rapid absorption onto the cement particles. In spite of this product being designed for Portland-cement based binders, this acceleration is evident in the results for lime-based binders as shown in Figure 23.

Figure 24 shows the compressive strength development of NHL2-, NHL3.5- and NHL5-mortars of equal flow. Additionally the strength development of three lime-pozzolan mortars (also prepared with G3) has been plotted for comparison. For completeness the strength development a NHL5 reference mortar prepared with the same aggregates but without any SP [1] has also been shown.

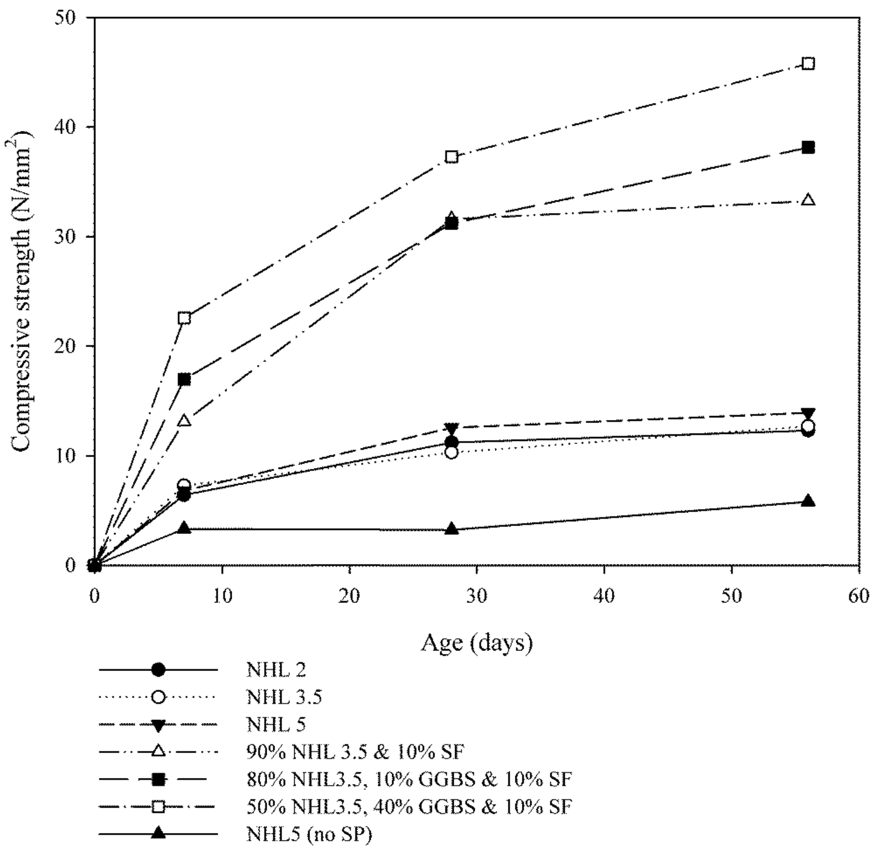


Figure 24: Compressive strength development of hydraulic lime mortars with and without SPs and aluminosilicate mineral additions

It can be seen from Figure 24 that there is little to differentiate the strength development of the three superplasticised hydraulic lime mortars (NHL2, NHL3.5 and NHL5), which attained 28-day strengths of 11.2, 10.3 and 12.6 MPa respectively. The strength of the eminently hydraulic lime mortar (NHL5) is observed to be marginally higher at both 28-day and 56-days. However, considering the strength development of the NHL5 reference mortar (without SP) the addition of SP can be seen to have a marked impact on the compressive strength of the lime-mortars. For example addition of 1.2% G3 was seen to increase the 28-day strength of an NHL5 mortar from 3.2 to 12.6MPa. It is evident that the addition of SP substantially increases the compressive strength gain of the hydraulic lime mortars in the first 28-days. From 28-56 days the strength gain in the two NHL5 mortars, with and without SP, is seen to be comparable. The strength enhancement provided by the SP is consistent with studies of PC binders [30]. Dispersion of the particles not only improves the flow characteristics of the fresh paste, but positively effects the growth of the hydration products resulting in microstructural changes which improve mechanical strength. Plank and Hirsh (2007) have investigated the effect of PCE on the hydration of PC systems, finding that PCE promotes crystal growth in the interstitial pore spaces, reducing the mean pore size and porosity of the hardened paste [30].

Furthermore the results in Figure 24 show that the strength increase associated with the addition of SP is further enhanced by the strength gain associated with inclusion of the pozzolanic addition. Inclusion of 10% SF in the NHL3.5 mortar resulted in a 28-day compressive strength of 31.6MPa, three times the strength attained by the NHL 3.5 alone (10.3MPa). A ternary blend of 10% SF and 10% GGBS further improved the compressive strength at 7 and 56 days but the greatest increase in compressive strength was attained in the mortar prepared with 50% NHL 3.5, 40% GGBS and 10% SF. At 28-days the compressive strength this mortar was 37.3 MPa, 3.6 times higher than the equivalent mortar prepared with NHL 3.5 alone.

Given that there was little to differentiate the strength development of the three hydraulic lime mortars (NHL2, NHL3.5 and NHL5), it would be interesting to investigate the relative performance of the three hydraulic limes in combination with pozzolanic additions.

The strength development of lime-pozzolan mortars prepared with different lime types needs to be monitored over a longer time period, in order to investigate the contribution of the hydraulic and pozzolanic reactions to long term strength development. In PC binders the hydration of alite is fast and the $Ca(OH)_2$ produced by the reaction then induces a high enough pH to dissolve the silica and alumina and initiate the pozzolanic reaction [31]. Although the hydration of belite also produces $Ca(OH)_2$, the hydration reaction is slow and $Ca(OH)_2$ is already available as a major constituent of the hydraulic lime. With a highly reactive pozzolanic addition such as SF, the pozzolanic reaction is therefore likely to dominate initially, producing C-S-H. The strength development of hydraulic limes in combination with pozzolanic additions will therefore depend on the initiation, duration and extent of the two competing reactions as well as the nature and locality of the C-S-H crystals produced by both reactions.

With regard to broader aims of this experimental investigation, namely to investigate the feasibility of producing a modern structural-strength lime-pozzolan concrete, the production of an air-cured lime-pozzolan mortar with a 28-day compressive strength of 37MPa, increasing to 45MPa at 56 days, was considered a significant step forward and had the potential to meet the demands of the doubly curved ‘lime concrete’ shell roof which was the ‘real-world’ driver for the laboratory study. This lime-mortar comprised 50% NHL3.5, 40% GGS & 10% SF. Considering 28-day compressive strengths of air-cured specimens, results of a previous study have evidenced a 2.5-3.5MPa increase in compressive strength when mixes are scaled from mortars to concretes [1] & [2]. This indicated the potential for a lime-pozzolan concrete with a 28-day air-cured strength of around 40MPa.

Study 2: Enhancing the composition of the ternary lime-pozzolan binder

Table 14 reports the mechanical properties of four lime-pozzolan concretes. In addition to compressive strength development the cylinder strength (f_{cyl}), elastic modulus (E_c), compressive strain at the maximum stress (ε_{c1}) and nominal ultimate strain (ε_{cu1}) of each of the four lime-pozzolan concretes is also reported.

Table 14: Mechanical properties of lime-pozzolan concretes

Mix description	w/b	F_c (MPa)				F_{cyl28}	F_{cyl}/F_c	E_c	ε_{c1}	ε_{cu1}
	day	7	28	56	90	Mpa		GPa		
68% NHL5, 20% GGBS, 12% SF (I)	0.42	19.1	34.2	37.6	40.4	30.5	0.89	19.0	0.004	0.005
50% NHL5, 40% GGBS, 10% SF (II)	0.35	27.6	49.4	53.0	58.3	41.5	0.84	20.0	0.003	0.005
60% NHL5, 30% GGBS, 11% SF (III)	0.37	27.0	44.2	50.3	53.4	39.1	0.89	24.5	0.003	0.003
56% NHL5, 34% GGBS, 10% SF (IV)	0.35	31.3	49.2	57.6	64.9	49.1	1.00	20.5	0.003	0.007

The maximum 28-day compressive strength of the four lime-pozzolan concretes was 49.4 MPa. All four of the lime-pozzolan concretes attained a 28-day cube strength greater than

30MPa (the minimum performance threshold identified at the outset of this research programme). Three of the four concretes attained a 28-day cube strength greater than 40MPa.

Mixes (II) and (IV) are directly comparable having been produced at the same w/b ratio and with the same proportion of SF. The two mixes both attained a cube strength of around 49MPa at 28-days, but mix (IV), which had a slightly higher proportion of NHL5, exhibited the greatest strength gain between 28 and 90 days reaching a cube strength of around 65MPa. It is observed that the increased proportion of NHL5, enhanced the compressive strength of the resultant concretes results at 7, 56 and 90-days, suggesting that the lime contributes to both the short and long-term strength gain of the concrete. A higher proportion of NHL5 will in the short-term provide more $Ca(OH)_2$ for activation of the pozzolanic reaction and in the longer-term provide more belite for hydration and $Ca(OH)_2$ for carbonation reactions.

The minimum ratio of F_{cyl}/F_{cube} observed is 0.84. This is higher than the factor of 0.8 assumed for converting cube to cylinder strengths in the design of concrete structures to EC2 [20]. Use of 0.8, in accordance with the code, will result in a conservative designation of the compressive strength of lime-pozzolan concretes in design. The elastic moduli of these four lime-pozzolan concretes ranged between 19 and 24GPa. The strain at the maximum stress in all four concretes was 0.003 or above.

This testing has demonstrated that it is possible for a ternary lime-pozzolan concrete (56% NHL5, 34% GGBS & 10% SF) to attain a 28-day compressive strength of 49MPa increasing to 65 MPa at 90-days. It has not been possible to draw any conclusions from the results about the effect of the ratio of GGBS:lime due to the variation of w/b ratio of the produced mixes.

Study 3: The influence of cold-weather on compressive strength development

The cube strength of identical lime-pozzolan specimens cured in either the conditioning lab (maintained at 20±0.5°C and 60-65% RH) or alternatively in ambient winter-weather conditions are reported in Table 15.

Table 15: Strength development of lime-pozzolan concretes cured in alternative conditions

Mix description	Average cube strength of specimens cured at 20±0.5°C and 60-65% RH (MPa)		Average cube strength of specimens cured in varibale winter-weather conditions (MPa)		% strength reduction	
day	28	56	28	56	28	56
68% NHL5, 20% GGBS, 12% SF (I)	34.2	37.6	19.1	26.0	44%	31%
50% NHL5, 40% GGBS, 10% SF (II)	49.4	53.0	31.5	35.4	36%	33%
60% NHL5, 30% GGBS, 11% SF (III)	44.2	50.3	29.9	33.3	32%	34%
56% NHL5, 34% GGBS, 10% SF (IV)	49.2	57.6	34.1	42.5	31%	26%

It is observed from these results that cold-weather curing reduces the 28-day strength of lime-pozzolan concretes by up to 44%. A previous study looking at the effect of cold temperature curing on the strength development of PC-concretes, has shown a 28-day strength reduction of between 30% at 10°C and 50% at 0°C [32], which suggests that cold weather is similarly detrimental in the curing of both PC and lime-based concretes. This study of PC-concretes showed that concretes cured at 0°C evidenced a strength reduction of 62% at 7-days. Given the slower rate of hydration of lime-based concretes, the 7-day strength reduction might be expected to exceed 62%. Typically the strength reduction associated with cold-weather-curing is seen to be less critical at 56-days.

Study 4: Flexural behaviour of reinforced lime-pozzolan concrete beams

The compressive strength development of the lime-pozzolan concrete used for fabrication of the two beams is shown in Table 16. The 28-day flexural strength of this concrete was found to be 3.7MPa, which is in line with the expected flexural strength of PC concretes made with limestone aggregates [33].

Table 16: Compressive strength development and flexural strength of beam lime-pozzolan concrete

days	**28**	**56**	**90**	**180**
Mean compressiove strength, Mpa	40.7	47.3	52.8	56.6
Flexural strength, Mpa	3.7			

Table 17 gives the ultimate load capacity and failure mode of each of the four concrete beams tested in 3-point bending. The theoretical capacity (predicted in accordance with EC2 [20]) for each of each of the four beams is also shown. A conservative triangular stress distribution was assumed for the calculation of the flexural capacity of lime-pozzolan concrete, assuming a maximum concrete strain of 0.003. All the material safety factors were removed from the design code, when calculating the theoretical capacity of the lime-pozzolan concrete beams.

Table 17: Ultimate load capacities and failure modes for the four concrete beams

Beam	Concrete cube strength, f_{cu28}	EC2 moment capacity	EC2 shear capacity	Point load corresponding to max moment	Point load corresponding to max shear	Anticipated failure mode	Total applied ultimate load, P_u	Actual failure mode	Ratio of predicted to actual
	MPa	kNm	kN	kN	kN		kN		
LP_A	40.2	19.7	16.9	28.1	33.8	*flexure*	31.0	*flexure*	1.102
LP_B	35.0	26.9	20.4	38.4	40.8	*flexure*	44.0	*shear*	1.145
PC_A	41.2	18.9	17.3	27.0	34.6	*flexure*	30.6	*flexure*	1.133
PC_B	35.0	33.9	21.0	48.4	42.0	*shear*	45.3	*shear*	1.079

The load-mid-span deflection plots for the four concrete beams are shown in Figure 25.

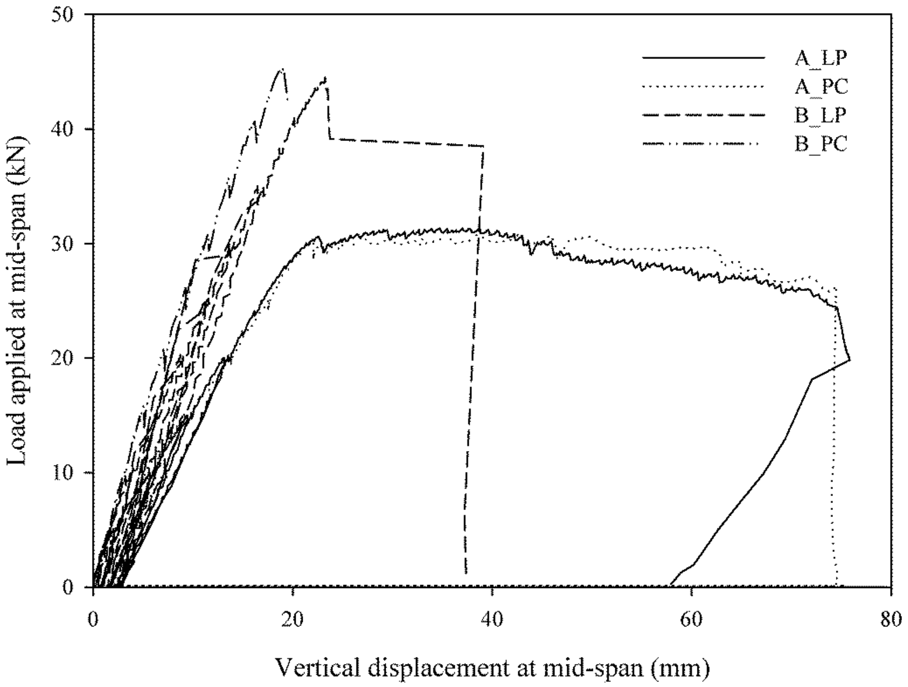
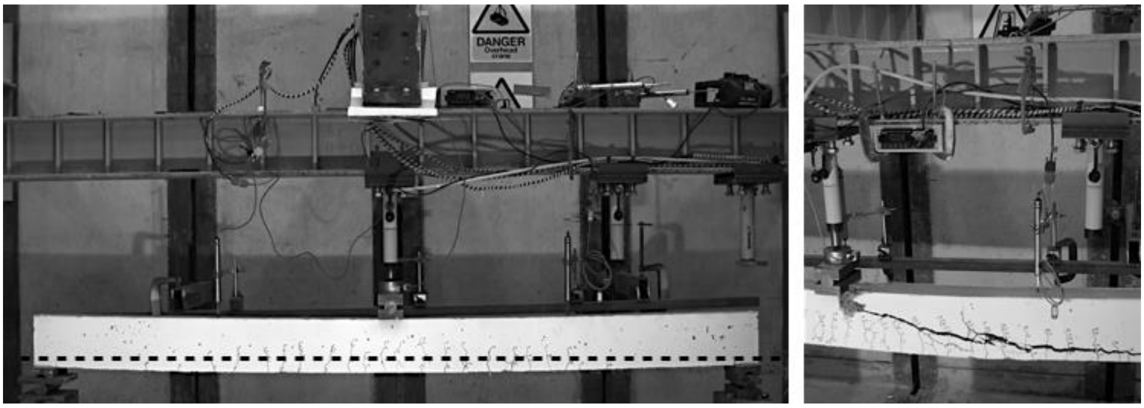


Figure 25: Load mid-span deflection plot for the lime-pozzolan and PC beamsLoad mid-span deflection plot for the lime-pozzolan and PC beams

In the case of the under reinforced lime-pozzolan concrete beam (LP_A) flexural cracking was first observed and traced onto the beam at an applied load of 5 kN; the mid-span deflection was 2.1 mm. On removal of the load the beam recovered 1.4mm of the initial deflection. The beam failed in a ductile manner with localised spalling of the top cover providing evidence of gradual crushing in the compression zone. The beam sustained a total applied load at mid-span of 31.3kN, under which load it had deflected 34.7mm. Yielding of the tension steel resulted in a maximum deflection of 75.8mm at mid-span. The curvature of the beam can be seen in Figure 26 (a).

In the case of the over reinforced lime-pozzolan concrete beam (LP_B) flexural cracking was first observed and traced onto the beam at an applied load of 5.0kN having deflected 1.6 mm at mid-span. On removal of the load the beam recovered 1.1mm of the initial deflection. The beam sustained a maximum applied load at mid-span of 44.5kN, having deflected 23.7mm. The beam failed in shear in a brittle manner. The rapidly forming shear crack can be seen in Figure 26(b).



(a) **(b)**

Figure 26: Photos of lime-pozzolan beams LP_A (a) and LP_B (b)

With regard to the beam testing to the following points may be made:

a) In both the under- and over-reinforced beams the flexural behaviour of the lime-pozzolan concrete beams was observed to be similar to that of the PC control beams. The similarity in the flexural behaviour of the lime- and PC-concrete beams suggested that bond characteristics were similar. In the case of the over-reinforced lime-pozzolan concrete beam (LP_B) the central deflection at the point of failure was almost 50mm, 40% higher than the equivalent deflection of the equivalent beam, PC_B, (35mm). This flexural behaviour might have resulted from the lower elastic modulus of the lime-pozzolan concrete. The increased deflection observed in the lime-pozzolan concrete beams suggested that some modification might be appropriate in the serviceability limit state (SLS) design of lime-pozzolan concrete structures.

b) The ratio of the predicted to actual beam failure load was greater than 1.0 in the case of each beam, suggesting that the fundamental principles for the design of concrete structures, embodied in EC2 [20], might be employed for the conservative design of structural lime-pozzolan elements. In the case of the over-reinforced lime-pozzolan beam (LP_B), the beam was anticipated to fail in flexure as opposed to shear based on the calculated moment and shear capacity (shown in Table 17). The actual shear failure of the beam implied that the use of a triangular stress distribution in the calculation of the flexural capacity of the beam had been overly conservative. In reality a reinforced lime-pozzolan concrete beam, would be under-reinforced and specified with shear links to prevent this brittle mode of failure.

Flexural testing of two reinforced lime-pozzolan concrete beams has demonstrated that lime-pozzolan concretes can indeed be cast into structural elements with a finished surface and appearance similar to PC-concrete. Furthermore the results indicate that EC2 can be used for the conservative design of reinforced lime-pozzolan structural elements, with appropriate substitution of material properties into the design process. Clearly further structural testing is needed to inform the safe and design of efficient design of lime-pozzolan concrete structures in the future. A conservative design approach for new materials is described in BS EN 1990:2002+A1:2005 [34], based on a statistical determination of material strength using a limited number of laboratory results. This conservative approach was adopted in the structural design of the doubly-curved lime-pozzolan concrete shell roof.

Conclusions

The overall objective of this study was to develop a structural lime-pozzolan concrete suitable for adoption on a real-world construction project. The explicit and upfront objective of a ‘real world’ solution fostered an engineering design approach to the research, which focused on addressing a number of issues arising from the potential adoption of the technology. The laboratory testing and development outlined in this paper is purported to demonstrate the feasibility of producing structural hydraulic lime-pozzolan concretes.

Identification of an effective superplasticiser enabled the production of two reinforced lime-pozzolan concrete beams, with an appearance and flexural behaviour similar to Portland-cement concrete. The addition of SP was shown not only to improve the workability of the fresh lime-pozzolan concrete but also to substantially enhance the compressive strength of the hardened concrete. A maximum 28-day compressive strength of 49MPa was attained by ternary lime-pozzolan concretes comprising 10% SF and either 56% NHL5 and 34% GGBS or 50% NHL5 and 40% GGBS, cured in air.

Detailed investigation has led to the following conclusions:

i. It has been shown that a number of commercially available PCE superplasticisers can be employed to produce workable and high strength lime-pozzolan concretes, however the required tended to be higher than that recommended for PC systems. Unlike in PC systems the addition of 10% SF tended to reduce the demand for SP, suggesting that the workability of the mix might then be dominated by effective dispersion of the SF particles.
ii. Addition of 1.2% SP was seen to increase the 28-day strength of an NHL5 mortar from 3.2 to 12.6MPa. A fourth-generation product, containing a synthetic co-polymer designed to accelerate the early age strength development of PC-concretes, was found to result in the highest strength lime-pozzolan mortars. The influence of alternative SPs on compressive strength development was seen to have the greatest impact in the first 7-days.
iii. Inclusion of 10% SF in the NHL3.5 mortar resulted in a 28-day compressive strength of 31.6MPa, three times the strength attained by the NHL 3.5 alone (10.3MPa).
iv. A ternary blend of 10% SF and 10% GGBS further improved the compressive strength at 7 and 56 days. The greatest increase in compressive strength was attained in the mortar prepared with 50% NHL 3.5, 40% GGBS and 10% SF. At 28-days the compressive strength this mortar was 37.3MPa, 3.6 times higher than the equivalent mortar prepared with NHL 3.5 alone.
v. The results have demonstrated that it is possible for a ternary lime-pozzolan concrete (56% NHL5, 34% GGBS & 10% SF) to attain an air-cured compressive strength of 49MPa at 28-days increasing to 65MPa at 90-days. All four of the lime-pozzolan concretes tested in this programme attained a 28-day cube strength greater than 30MPa (the minimum performance threshold identified at the outset of this research programme). Three of the four concretes attained a 28-day cube strength greater than 40MPa.
vi. It is observed from these results that cold-weather curing reduces the 28-day strength of lime-pozzolan concretes by up to 44%. This suggests that cold weather is similarly detrimental to the strength gain of both CEM1 and lime-pozzolan concretes.

vii. Flexural testing of two reinforced lime-pozzolan concrete beams has demonstrated that lime-pozzolan concretes can be cast into structural elements with a finished surface and appearance similar to CEM1-concrete. In the lime-pozzolan beams the central deflection at the point of failure was 40% higher than the equivalent deflection of the CEM1 concrete beams. This suggests that some modification may be appropriate in the serviceability limit state (SLS) design of lime-pozzolan concrete elements.

viii. The ratio of the predicted to actual beam failure load was greater than 1.0 in the case each lime-pozzolan concrete beam, suggesting that the fundamental principles for the design of concrete structures, embodied in EC2 [20], might be employed for the conservative design of structural lime-pozzolan elements.

This performance-driven research project was found to be effective in the rapid convergence on project-specific solution. However it is clear that this engineering-design approach, which focused on addressing specific field requirements, restricted the scope of the scientific inquiry. As a result a number of additional questions have arisen, which might be key in the on-going development of lime-pozzolan concretes:

i. In comparison to the strength enhancement observed with the addition of 10% SF to an NHL3.5 mortar, there is little to differentiate the strength development of the three hydraulic lime mortars NHL2, NHL3.5 and NHL5. This raised a question about the relative performance of the three hydraulic limes in combination with pozzolanic additions. The higher free lime content of NHL3.5, or NHL2, might further enable the pozzolanic reaction and enhance the lime-pozzolan binder. Given NHL3.5 has a lower embodied CO_2 and energy than NHL5 [35], the results suggest that this moderately-hydraulic lime warrants further investigation in the development of future lime-pozzolan binders. Such future testing might investigate how the use of NHL3.5 affects not only mechanical strength, but also the porosity and permeability of the resulting lime-pozzolan concretes.

ii. It is suggested that a blended PCE superplasticiser might in future be specifically designed for binary or ternary lime-pozzolan binders, which would minimise the overall required dosage and thus also the embodied impact of the resulting lime-pozzolan concrete. Specific modelling of the zeta potential of the constituent minerals in aqueous solution is thought to be required to understand the absorption mechanism of PCE superplasticisers in binary and ternary lime-pozzolan binders.

iii. With respect to the ratio of lime to GGBS in the ternary binder, it is acknowledged that this research has identified a sufficing solution. Future research could look to optimise this ratio, for a range of performance criteria.

Increasing industry-academic collaboration is not only challenging the normative models of scientific inquiry, but also changing the day to day experience of researchers who span boundaries of academia-industry. The bi-directional flow of queries, ideas and feedback between academia and industry creates a dynamic research environment, which requires a sensitive and flexible research approach. One day a new technology may be subjected to rigorous testing in the laboratory and the next it may be subject to the scrutiny of a professional design team, prospective customer or Building Control official. The evaluation of the technology in both environments is held to be equally valid, as both are equally significant in determining both the subsequent research step and thus ultimately the direction and future impact of the developing technology.

Given that this structural solution was sought as a ‘green’ alternative to Portland-cement solution, it is recognised that an in-depth assessment of the environmental performance of this material is necessary to justify and inform further testing. Reduced environmental impact, amongst other performance benefits, is anticipated to substantially affect industry interest in the adoption of this innovative concrete technology.

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Structural limecrete: an investigation into the potential of hydraulic lime-concrete using pozzolanic and latent hydraulic additions

Ellen Grist, EngD Research Engineer, Ramboll (ellen.grist@ramboll.co.uk)
Ramboll, 40 Queen Square, Bristol, BS1 4QP, UK

Introduction

The cement industry is reported to be responsible for about 5% of the total global anthropogenic carbon emissions. With the demand for cement growing year on year and increasingly efficient manufacturing technologies able to offer less and less savings, the hunt is on for alternative binders, and concretes, that are less carbon intensive [1].

The potential for a structural lime-concrete has been noted, '*The science of using lime concrete in a similar way to Portland Cement concrete for structural frames has not been developed. There is however, considerable potential for further research and development of lime concrete for its application as an appropriate building technology*'[2]. More recently, a review of 'industrially interesting approaches to "low-CO2" cements', highlighted the potential for developing clinkers '*with a lower alite and higher belite content*'[3]. Belite, the predominant hydraulic compound in NHL5, is both produced at a lower kiln temperature to alite (the predominate hydraulic compound in Portland cement) and requires less raw material feedstock.

Recent research into the production of hydraulic lime-concretes has reported maximum 28-day cube strengths of 16N/mm^{2,} cured at 65% RH[4]. However, the research reported in this paper has demonstrated that it is possible to attain 28-day cube strengths of approximately 50N/mm^2 at 65% RH, by combining natural hydraulic lime with amorphous aluminosilicate industrial by-products. The feasibility of attaining strengths comparable with Portland cement concretes is thought to be a step-change for research in this area.

This paper presents an overview of the research conducted at the University of Bath, highlighting the key results. Two industry projects are briefly introduced to contextualise the research intent and to qualify the potential impact of the findings.

Context

This research project was initiated by an architect who envisioned a lime-concrete shell roof for a private residence in the Cotswolds. This innovative structural solution was central to a planning application, which demanded a 'truly outstanding and groundbreaking' scheme[5]. Demand led, this industry based research programme continues to be shaped by individuals and organisations with an interest in the developing technology.

Most recently a bespoke polished lime-concrete floor screed has been developed for a school in Bath. The material was adapted to incorporate frost-shattered limestone, taken from the school site, as a sustainable aggregate. Trials undertaken, in conjunction with a specialist contractor, demonstrated the feasibility of polishing the lime-concrete to expose the site material as a decorative surface finish.

Such applications have only been rendered conceivable, by the high early strength gain that this research project has demonstrated is achievable in ambient conditions. The slow-strength gain which is so commonly associated with the use of lime in construction, is likely to remain a barrier to the adoption of lime-concretes long after the contrary has been demonstrated in the laboratory.

It should be noted that before the advent of Portland cement in 1824 that lime was the predominant binder for use in construction. The time-honoured practice of 'gauging' lime mortars, and concretes, with pozzolanic materials, originated with the Greeks[6]. Many ancient Greek, and Roman structures, most famously the Pantheon, remain today and are a testament to the durability of lime-concretes. However, the research described in this paper does not reflect a return to former technologies, but rather builds upon the substantial developments in concrete technology that have taken place in recent years. Specifically the development and utilisation of highly reactive pozzolans (e.g. silica fume) and the development of polycarboxylate-ether based superpalasticizers and other admixtures.

Materials

This research was conducted using naturally hydraulic lime (NHL5) from St. Astier in France. Such eminently hydraulic limes are no longer manufactured in the UK. The pozzolanic and latent hydraulic additions that have been used in this investigation include: silica fume, fly ash, ground-granulated blastfurnace slag, metakaolin and brick dust. The lime-concrete samples were typically prepared using a siliceous sand and a carboniferous limestone aggregate, both of which were dried to a lab-dry state before use.

Experimental method and key findings

There were a large number of possible pozzolanic and hydraulic additions, and combinations thereof, which were identified as potential options for the partial replacement of the NHL5 (by weight). Testing, of twenty-two lime mortar mixes, was used to identify four promising blends, which yielded the highest compressive strengths. A large range of strengths, tested at 7, 28, 56 and 90 days, demonstrated the relative contribution of the different additions. The majority of the additions were seen to have a beneficial affect on strength development, outperforming mortars prepared with NHL5 alone. A number of the mortars were substantially stronger over a 28 day period.

Four of these promising mixes were then scaled up to investigate the affect of the water-to-binder (w/b) ratio and curing regime on the strength and durability of the resulting lime-concretes. As well as strength development, testing also considered the linear shrinkage, rate of carbonation and elastic modulus of the samples. Considering both the mechanical performance and the commercial viability of the mixes, a single combination of additions was selected for further trials.

Much like concrete the (w/b) ratio has been shown to have a significant affect on the resultant strength, with higher strengths achieved at lower w/b ratios. Achieving a workable fresh material at a low w/b ratio necessitated an additional investigation into the relative performance of a range of superplasticisers. Although the familiar slump test is still thought to be a poor indicator of the workability of fresh lime-concrete, a suitable proprietary polycarboxylate-ether based superplasticiser was identified that produced a workable and compactable material, when prepared at a w/b ratio of 0.35.

Since maximum strength and minimal environmental impact were the overarching goals of the research, the mix design and testing programme benefited from the insight of a range of industry stakeholders and modifications to both were made along the way. The inclusion of the superplasticiser was seen to have a marked improvement of the cube strength of the material, and 28-day strengths in excess of $49N/mm^2$ were achieved. This was a real break through, paving the way for the production and testing of two 3m long reinforced lime-concrete beams.

The two beams were both prepared with the same lime-concrete mix, but one over- and one under-reinforced to assess the structural behaviour of the two beams in bending. The beams were tested 28 days after casting, having been cured in the laboratory at ambient temperature and humidity for this period. The predicted failure load of each beam was calculated using Eurocode 2 [7], substituting in the material properties, ascertained in the lab, and modifying the stress and strain distributions accordingly. Comparing the predicted failure loads with the actual failure loads, demonstrated the suitability of standard concrete design codes for designing lime-concrete elements.

Beam Reference	**28-day Cube Strength (N/mm^2)**	**Theoretical maximum point load at mid-span (kN)**	**Failure load, applied at mid-span (kN)**
Under-reinforced *(2no. H12 bars)*	40	27	31
Over-reinforced *(4no. H12 bars)*	40	44	44

Table 1: Results of reinforced lime-concrete beam testing

This larger-scale structural test, importantly, gave engineer's in Ramboll, the results needed to confidently design and substantiate the lime-concrete shell roof for the project in the Cotswolds. The results of testing in the laboratory and the calculation package, rather unusually, became a key part of the planning application for this building. At the time of writing the scheme is awaiting planning permission.

Discussion and conclusions

Having demonstrated the feasibility of a structural grade lime-concrete, thoughts have turned to it's potential application, beyond the scope of the two projects for which it has been specifically developed. With the provincial lime industry all but eradicated by the growth of industrial cement manufacture in the 19th century, it is recognised that the production capacity of the lime-industry is dwarfed by that of the cement-industry. For example in 2011 France, a primary lime producer in Europe, produced around 300,000 tonnes of hydraulic lime and around 24 million tonnes of cement (St Astier, *pers.comm.* April 2012). By that same token the global lime industry is not under pressure, nor incentivised, to invest in new technologies that might improve the efficiency of current manufacturing processes. It is thought that potential energy savings, associated with the production of lime at lower kiln temperatures, are not currently being exploited and that the alleged environmental benefits of lime are in some cases future-orientated. If true, this represents a significant opportunity for growth in this material and industry.

The economies of scale that result in the relatively inexpensive production of cement, are thought will preclude lime based construction materials from competing in a mainstream market for the foreseeable future. However the growing market for 'green' materials does create opportunities for bringing lime-based products to market and extending the possible application and demand for these materials.

The lime-concrete mix developed for the shell roof is estimated to have an embodied carbon of 195kg of CO_2/m^3. The embodied CO_2 figures for the constituent materials used in the approximation are as follows: NHL5 (635 $kgCO_2$/tonne), SF (14 $kgCO_2$/tonne), GGBS (52 $kgCO_2$/tonne) as supplied by manufacturers. Despite having a higher overall binder content, the embodied CO_2 of this lime-concrete, compares favourably with both CEM1 concrete (285 $kgCO_2/m^3$) and typical 'UK Concrete' (225 $kgCO_2$/m3)†[8]. Further reductions in the embodied carbon of lime-concrete would be realised if the initial free water content could be reduced.

In the context of an industry responsible for the production for around 1.5 billion tonnes of CO_2 per year, even modest reductions in the embodied carbon of cementitious materials has the potential to save hundreds of millions of tonnes of carbon emissions every year. In the light of this, the potential savings are thought to derive less from the precise composition of alternatives materials and more from the scale at which alternative technologies are adopted in practise. It is anticipated that the total carbon emissions, associated with lime manufacture could be reduced, and that alternative pozzolanic additions may be found that increase the scope of lime-based concretes to make a significant difference to the global community.

Further work

A reduced environmental impact is not thought to be the only potential advantage of the use of lime-concrete in construction. Other benefits are likely to result from other material properties, which differentiate lime-concretes from cement-concretes, including the elastic behaviour, breathability and durability of this material. Further testing is required to qualify these properties and their benefits in specific building applications.

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† based on the weighted average embodied carbon of all the CEM I, II, III, and IV supplied in the UK, in 2008.

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This research was conducted using naturally hydraulic lime (NHL5) from St. Astier in France. Such eminently hydraulic limes are no longer manufactured in the UK. The pozzolanic and latent hydraulic additions that have been used in this investigation include: silica fume, fly ash, ground-granulated blastfurnace slag, metakaolin and brick dust. The lime-concrete samples were typically prepared using a siliceous sand and a carboniferous limestone aggregate, both of which were dried to a lab-dry state before use.

Experimental method and key findings

There were a large number of possible pozzolanic and hydraulic additions, and combinations thereof, which were identified as potential options for the partial replacement of the NHL5 (by weight). Testing, of twenty-two lime mortar mixes, was used to identify four promising blends, which yielded the highest compressive strengths. A large range of strengths, tested at 7, 28, 56 and 90 days, demonstrated the relative contribution of the different additions. The majority of the additions were seen to have a beneficial affect on strength development, outperforming mortars prepared with NHL5 alone. A number of the mortars were substantially stronger over a 28 day period.

Four of these promising mixes were then scaled up to investigate the affect of the water-to-binder (w/b) ratio and curing regime on the strength and durability of the resulting lime-concretes. As well as strength development, testing also considered the linear shrinkage, rate of carbonation and elastic modulus of the samples. Considering both the mechanical performance and the commercial viability of the mixes, a single combination of additions was selected for further trials.

Much like concrete the (w/b) ratio has been shown to have a significant affect on the resultant strength, with higher strengths achieved at lower w/b ratios. Achieving a workable fresh material at a low w/b ratio necessitated an additional investigation into the relative performance of a range of superplasticisers. Although the familiar slump test is still thought to be a poor indicator of the workability of fresh lime-concrete, a suitable proprietary polycarboxylate-ether based superplasticiser was identified that produced a workable and compactable material, when prepared at a w/b ratio of 0.35.

Since maximum strength and minimal environmental impact were the overarching goals of the research, the mix design and testing programme benefited from the insight of a range of industry stakeholders and modifications to both were made along the way. The inclusion of the superplasticiser was seen to have a marked improvement of the cube strength of the material, and 28-day strengths in excess of 49N/mm^2 were achieved. This was a real break through, paving the way for the production and testing of two 3m long reinforced lime-concrete beams.

The two beams were both prepared with the same lime-concrete mix, but one over- and one under-reinforced to assess the structural behaviour of the two beams in bending. The beams were tested 28 days after casting, having been cured in the laboratory at ambient temperature and humidity for this period. The predicted failure load of each beam was calculated using Eurocode 2 [7], substituting in the material properties, ascertained in the lab, and modifying the stress and strain distributions accordingly. Comparing the predicted failure loads with the actual failure loads, demonstrated the suitability of standard concrete design codes for designing lime-concrete elements.

Beam Reference	**28-day Cube Strength (N/mm^2)**	**Theoretical maximum point load at mid-span (kN)**	**Failure load, applied at mid-span (kN)**
Under-reinforced *(2no. H12 bars)*	40	27	31
Over-reinforced *(4no. H12 bars)*	40	44	44

Table 1: Results of reinforced lime-concrete beam testing

This larger-scale structural test, importantly, gave engineer's in Ramboll, the results needed to confidently design and substantiate the lime-concrete shell roof for the project in the Cotswolds. The results of testing in the laboratory and the calculation package, rather unusually, became a key part of the planning application for this building. At the time of writing the scheme is awaiting planning permission.

Discussion and conclusions

Having demonstrated the feasibility of a structural grade lime-concrete, thoughts have turned to it's potential application, beyond the scope of the two projects for which it has been specifically developed. With the provincial lime industry all but eradicated by the growth of industrial cement manufacture in the 19th century, it is recognised that the production capacity of the lime-industry is dwarfed by that of the cement-industry. For example in 2011 France, a primary lime producer in Europe, produced around 300,000 tonnes of hydraulic lime and around 24 million tonnes of cement (St Astier, *pers.comm.* April 2012). By that same token the global lime industry is not under pressure, nor incentivised, to invest in new technologies that might improve the efficiency of current manufacturing processes. It is thought that potential energy savings, associated with the production of lime at lower kiln temperatures, are not currently being exploited and that the alleged environmental benefits of lime are in some cases future-orientated. If true, this represents a significant opportunity for growth in this material and industry.

The economies of scale that result in the relatively inexpensive production of cement, are thought will preclude lime based construction materials from competing in a mainstream market for the foreseeable future. However the growing market for 'green' materials does create opportunities for bringing lime-based products to market and extending the possible application and demand for these materials.

The lime-concrete mix developed for the shell roof is estimated to have an embodied carbon of 195kg of CO_2/m^3. The embodied CO_2 figures for the constituent materials used in the approximation are as follows: NHL5 (635 $kgCO_2$/tonne), SF (14 $kgCO_2$/tonne), GGBS (52 $kgCO_2$/tonne) as supplied by manufacturers. Despite having a higher overall binder content, the embodied CO_2 of this lime-concrete, compares favourably with both CEM1 concrete (285 $kgCO_2/m^3$) and typical 'UK Concrete' (225 $kgCO_2$/m3)†[8]. Further reductions in the embodied carbon of lime-concrete would be realised if the initial free water content could be reduced.

In the context of an industry responsible for the production for around 1.5 billion tonnes of CO_2 per year, even modest reductions in the embodied carbon of cementitious materials has the potential to save hundreds of millions of tonnes of carbon emissions every year. In the light of this, the potential savings are thought to derive less from the precise composition of alternatives materials and more from the scale at which alternative technologies are adopted in practise. It is anticipated that the total carbon emissions, associated with lime manufacture could be reduced, and that alternative pozzolanic additions may be found that increase the scope of lime-based concretes to make a significant difference to the global community.

Further work

A reduced environmental impact is not thought to be the only potential advantage of the use of lime-concrete in construction. Other benefits are likely to result from other material properties, which differentiate lime-concretes from cement-concretes, including the elastic behaviour, breathability and durability of this material. Further testing is required to qualify these properties and their benefits in specific building applications.

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† based on the weighted average embodied carbon of all the CEM I, II, III, and IV supplied in the UK, in 2008.

AN INVESTIGATION INTO THE VIABILITY AND BENEFITS OF MODERN HYDRAULIC LIME CONCRETES

E R Grist[1,2], K A Paine[2], A Heath[2], H Pinder[1]

1.Ramboll UK
2. University of Bath, UK

ABSTRACT Work undertaken at the University of Bath has demonstrated the feasibility of producing a lime-pozzolan concrete with a 28-day cube strength of around 50 N/mm^2 and an elastic modulus of 20GPa. The research has applied the substantial recent developments in concrete technology to a cementitious system that has proved its durability for more than 2000 years. Furthermore, production and testing of two reinforced lime-concrete beams has demonstrated the possibility of producing structural elements with a finished appearance and flexural behaviour similar to Portland cement concrete. Whilst it can be done, there remains a question as to whether it is worth doing. This paper reflects on the value of these results in the context of the industry wide search for low carbon cements. Use of aluminosilicate by-products, specifically ground granulated blastfurnace slag and silica fume, in combination with naturally hydraulic lime is thought to realise substantial savings in embodied impact, but it is recognised that the potential savings are highly dependent on the boundaries of the analysis and the case-specific application of this technology in practice. By considering a real case study project, designed in conjunction with Ramboll, a multidisciplinary engineering and design consultancy, this paper compares the embodied impact of an innovative lime-pozzolan concrete solution to a traditional Portland-cement alternative. Recognising that there are numerous barriers for the uptake of new cementitious materials in construction, this paper discusses the desirability and viability of this emerging lime-pozzolan technology.

Keywords: Sustainability, hydraulic-lime concrete, embodied CO_2

Ellen Grist is an EngD Research Engineer in the BRE Centre for Innovative Construction Materials at the University of Bath. Her research considers the uptake of innovative, sustainable materials in real-world construction projects. Ellen is conducting her research in industry and is based at her sponsoring company Ramboll UK.

Dr Kevin Paine is a Senior Lecturer in the BRE Centre for Innovative Construction Materials at the University of Bath. His research focuses on sustainable concrete technology.

Dr Andrew Heath is a Senior Lecturer in the BRE Centre for Innovative Construction Materials at the University of Bath. His research focuses on soil and sustainable construction.

Henry Pinder is a Design Engineer for Ramboll UK. He has been project engineer on the case-study project introduced in this paper.

INTRODUCTION

In 2011 over 3.4 billion tonnes of cement were produced worldwide [1] enough to produce over 11 billion m^3 of concrete or $1.6m^3$ for every man, woman and child on the planet. Although often vilified on environmental grounds, cement as the principal binding constituent of concrete, continues to be a key driving force of human development.

In 2011 the UK produced 8.5 million tonnes of cement and imported a further 84,000 tonnes [2]. In the same year India produced over 220 million tonnes of cement, being the second largest cement producer behind China whose annual production exceeded 2 billion tonnes [3]. The cement industry in India is experiencing strong growth due to the boom in real estate and government spending on infrastructure [4]. Annual production has grown from 95 million tonnes in 2000, with demand forecast to be between 646 and 1,649 million tonnes in 2050, across a range of high growth and target-driven growth scenarios [5].

The manufacture of Portland cement (CEMI) is an energy intensive process and is widely acknowledged to be responsible for 5-8% of the total global anthropogenic carbon emissions. The actual energy demand and energy related emissions vary significantly between production facilities, due to differing processing technology and national energy generation strategies. Japan pioneers energy-efficiency in cement kiln technology and boasts dry-process kilns with suspension pre-heaters and pre-calciners requiring less than 3000MJ/t clinker [6]. This is less than half the heat requirement of the older wet-kiln technology that demanded up to 6300MJ/t [7]. In 2007 the Indian cement industry was reported to comprise 148 large and 365 mini cement plants, the larger of which were reported to be amongst the most energy efficient production facilities in the world. The average heat demand for production of cement in India is 3200MJ/t [5] well below the global average of 3500-3600MJ/t [7].

Despite pressure to reduce its environmental impact the global cement industry must continue to invest in capacity expansion programmes in order to meet the growing demand. Investment in modern production technologies both minimizes the environmental impact and maximizes profitability for the cement producer. However with an upper limit on the overall kiln efficiency the returns associated with the investment in the best available technologies (BAT)'s are diminishing. Production efficiency is therefore not the only strategy for reducing the impact of cement manufacture on the natural environment. Other strategies include alternative fuel sources, carbon-capture and storage and the development of alternative cements.

ALTERNATIVE CEMENTS

One of CEMI's greatest strengths as a cement has been the widespread availability of raw materials for global production and the wide scale applicability of the material in use. With no other single cement technology set to succeed it, a shift in product mix is anticipated with a number of 'second generation', 'low-carbon' cements being developed. Potential second-generation cements that are in different stages of research and development include: calcium sulfoaluminate cements (CSAC) [8], supersulfated cements (SCC) [9], alkali activated cements and geopolymers [10], magnesium oxide cements [11], high volume slag cements [12], ternary cements [13] and as well as hydraulic lime-pozzolan cements.

With a total installed capacity of 3.2 billion tonnes of clinker and modern construction practice entirely geared to the production and use of Portland cement, novel cements face a very difficult route to market. It is however appreciable that it is the strength and ease of placement of concrete that is so fundamental to construction and not the nature of the cementitious binder itself.

Rising fuel costs, carbon reduction targets and a growing demand for more sustainable alternatives are driving change and forward-thinking cement manufacturers are getting ready to respond with new product technologies. Commenting in a special feature on emerging low carbon cements, Professor Pal Chana of MPA cement has argued that "there is a future for new or novel cements…but there really is a long way to go before they can make substantial inroads into the market" [14]. To envisage the 'post-Portland cement age' material scientists, contractors and consumers alike, need the ability to make sense of the benefits of alternative technological solutions. Against this backdrop this paper specifically reflects on the viability and potential of lime-pozzolan cements as a sustainable alternative to CEMI based cements.

HYDRAULIC LIME CONCRETE

Lime-pozzolan binders have a long history; a lime-concrete floor slab discovered in Southern Israel in 1985 was dated back to 7000BC [15]. However, the research reported in this paper does not represent a return to a former technology, as it exploits carefully produced and controlled pozzolanic materials and takes advantage of the significant advances in the development of concrete technology, specifically the performance of cutting edge water reducing admixtures. That said the considerable precedence for the use of this binder in construction is a significant advantage in comparison to other novel cements. Therefore its long history - a testament to the durability of this material - should not be disregarded.

This hydraulic-lime based concrete discussed in this paper should not be confused with 'Limecrete™' a commercially available lime-concrete, suitable for low-grade structural applications such as shallow footings and ground bearing floor slabs. Rather, the hydraulic lime concretes produced at the University of Bath, have a 28-day compressive strengths of around 50N/mm^2, which is comparable with Portland cement concretes, and can be cast as elements with a similar finished appearance and structural behaviour.

It is important to note that lime-based concretes are unlikely to be an environmentally friendly alternative to cement-based concretes if a greater overall binder content, or overall volume of concrete, is need to achieve the same function. For this reason a compressive strength of 30N/mm^2, comparable with that of a low-strength cement-based concrete, has been considered a minimum performance threshold. Consequently, the hydraulic lime based binder used as an exemplar in this paper comprises 50% NHL5, an eminently hydraulic lime, 40% ground granulated blastfurnce slag (GGBS), and 10% silica fume. It has been developed following significant research at the University of Bath [16] and can be used to obtain concrete strengths up to 50 N/mm^2.

A detailed life-cycle assessment of all the constituent components of this innovative composite material is beyond the scope of this paper. Rather this paper offers the reader an opportunity to step back and consider the bigger picture, facilitating a higher-level comparison of the relative impacts and potential savings that create opportunities for further development of this technology.

LIME

Both cement and lime are manufactured by the calcination of a source of calcium carbonate (typically limestone) at high temperatures. Naturally hydraulic limes (NHL) are produced by burning siliceous or argillaceous limestone, that contain clay impurities; namely silica (4-16%), alumina (1-8%) and ferrite (0.3-6%) [17].

Although limestone is abundantly available across the globe, making up 10% of all sedimentary rock, the quality of the limestone depends on the geological situation of the deposit. Deposits of siliceous or argillaceous limestone of suitable quality for production of NHL and which occur in deposits of a suitable size for commercial extraction are far fewer.

At kiln temperatures in excess of 900°C calcium carbonate ($CaCO_3$) disassociates, the carbon dioxide (CO_2) being driven off to produce calcium oxide (CaO), commonly known as quicklime. Reaction of this quicklime with the silica occurring in the limestone produces active calcium silicate phases, which are responsible for the hydraulicity of NHL5; the most hydraulic according to EN standards.

Different calcium silicate phases form at different kiln temperatures and in different parts of the kiln. CEMI typically comprises four primary calcium silicates of which alite (C_3S) is the most predominant. All four active phases are unstable in the presence of water and react to form hydrates that are responsible for hardening and which are fundamental in determining the long term mechanical properties of concrete. Alite forms at kiln temperatures of above 1300°C and is responsible for the rapid set of CEMI. NHL5 by comparison contains only a trace amount of alite and the dominant compound is belite (C_2S). The mineralogical composition of NHL5 is shown alongside a typical CEMI in Table 1.

The differences in the stoichiometric reactions demonstrate the theoretical savings associated with the production of NHL. Expressed in terms of mass, every tonne of alite produced liberates 579kg CO_2, whereas every tonne of belite produced liberates 511kg CO_2 [18]. This suggests a potential 12% saving in the raw-material CO_2. Furthermore, since belite forms at a lower kiln temperature than alite, further energy and carbon savings result from calcination of the limestone at reduced kiln temperatures that require less fuel. The dissociation temperature of $CaCO_3$ is around 900°C although [19] suggests that higher temperatures are needed to release CO_2 from the core of the limestone. The vertical-shaft kilns used for production of NHL5 tend to operate at 1000°C [20]. This is substantially lower than the 1450°C which is needed for the calcination of limestone to produce the alite in CEMI; although some of the energy needed for the extra temperature may be recovered in the form of preheated air for fuel combustion [21].

Disintegration of quicklime during slaking substantially reduces the demand for finish grinding in comparison to CEMI, with only 25% of the slaked lime coming out of the hydrator requiring further grinding. In Europe the total electricity consumption per tonne of CEMI is reported to be between 90-120 kWh, of which around 40% of this total (36-48 kWh) is required for grinding the clinker [7].

Table 1 Mineralogical composition of NHL5 in comparison to CEMI

COMPOUNDS	TYPICAL NHL5, % by mass	TYPICAL CEM I, % by mass
Insoluble content	4	trace
Free lime, $Ca(OH)_2$	21	2
Unburnt calcium carbonate ,$CaCO_3$	23	0
Alite, C_3S	trace	58
Belite, C_3S	45	13
Tricalcium aluminate, C_3A	2	9
Gehlenite, C_2AS	2	0
Calcium aluminoferrite, C_4AF	2	8
Gypsum, $CaSO_4$	trace	5
Other	1	5

The savings associated with the production of lime are discussed here as 'potential' savings as it is recognized that this smaller scale industry has not had the level of investment in production technology as the cement industry has and therefore is unlikely to be operating at the same kiln efficiencies. That said given that the production of lime, like cement, is based on the calcination of limestone, it is recognized that similar, or improved kiln efficiencies are possible in this industry.

OTHER CONSTIUENT MATERIALS

Technical performance alone cannot be used to assess, or compare, the merits of any new material. Rather consideration has to be given to the long-term feasibility and desirability of re-producing these cementitious systems in a commercial setting. This section focuses on the origin, availability and environmental performance of the aluminosilicate by-products, which are responsible for the mechanical properties of this concrete.

GGBS

GGBS is a latent hydraulic, Type II addition, sold as a 'high-quality, environmentally-friendly material, which is permitted to be used at up to 80% by mass of cement in Europe, and which improves many aspects of performance and reduces the embodied CO_2 of concrete.

GGBS is a by-product of the reduction of iron ore to produce metallurgical iron. Iron is manufactured by reduction of the ore, in the presence of carbon, in a blastfurnace at 1500°C. Molten which consists of the impurities in the ore and other 'slagging' agents, floats on the surface of the molten iron and both layers are regularly tapped out of the furnace. The molten slag that is to be processed for production of GGBS is rapidly quenched, by pouring it into a jet of cold water, to produce an amorphous granular material similar to coarse sand. This is then dried and then ground to the fineness of cement.

In 2011 global production of blastfurnace slag exceeded 770M tonnes. Hypothetically if all this blastfurnace slag could be sold as GGBS for cement replacement, it would still be less than 25% of the total mass of CEMI produced per annum. In reality the proportion of this blastfurnace slag that is suitable for granulation and production of GGBS is significantly less, with only 200M tonnes, or 26%, currently being sold as GGBS. Although it is difficult to determine the extent to which physical and economic factors will limit future production levels, it is clear that cementitious systems based on high replacement levels, or activation of GGBS, will not able to meet the total global requirement for sustainable binders.

The Concrete Centre reports that GGBS has an embodied CO_2 of 52 kgCO_2/tonne [22]. This figure includes the carbon associated with the secondary processes, namely granulation of the slag, transport to the slag grinding plant and carbon derived from drying and grinding. An equivalent embodied energy of 1300MJ is reported to include the production and distribution of electricity associated with these processes.

Silica Fume

Silica fume consists of spherical particles of amorphous silicon dioxide, SiO_2. Silica fume forms during the production of metallurgical grade silicon and ferrosilicon alloys. In both industrial processes quartz (a crystalline form of SiO_2) is reduced with a source of carbon, typically coal, coke or charcoal, in electric arc furnaces at temperatures in excess of 2000°C. One of the reduction reactions produces volatile silicon monoxide vapour, which is ejected from the stack. Oxidation of the silicon monoxide, at the top of the stack, produces silicon dioxide, which condenses into extremely fine 'smoke' particles of silica fume [23].

Silica-fume has been found to be a highly-reactive pozzolanic material, which improves both the rheology of fresh concrete and the strength and durability of the hardened material. Appreciation of the benefits of the use of silica fume as a supplementary cementitious material in the production of high strength concrete has seen the transition of this material from a polluting waste-product to a valuable by-product. Such is the market demand for silica fume today that plants will now run to produce silica fume in a down turn in alloy sales. Indeed high-purity, refractory grade silica fume is routinely produced with silicon-metal as a by-product.

The raw material for the production of silicon, quartz or quartzite, is abundantly available. As a by-product of the production of silicon metal and ferrosilicon alloys, the future availability of silica fume can reasonably be assessed by the projected demand for these two materials. Demand for these two products is principally driven by metal foundry industries, with ferrosilicon being a critical alloying component of iron in the production of steel [24] and silicon used similarly in the production of aluminium alloys.

A carbon foot-printing exercise commissioned by a silicon manufacturer and performed by a third party consultancy reports an embodied carbon of 14kgCO_2/tonne of silica fume slurry. This figure includes collection and secondary processing of the SF as well as transportation of the slurry to the UK [25]. No reliable source of data for the corresponding embodied energy of silica fume has been found. In the absence of such data an embodied energy value of 500MJ/kg has been assumed in calculations.

EMBODIED CARBON AND ENERGY OF HYDRAULIC LIME CONCRETE

When calculating the embodied energy of blended cements with supplementary cementitious materials great care has to be taken in the collection and allocation of the data. It is a relatively common practice in some studies to classify these materials as 'waste products' and thus attribute them with zero embodied carbon (EC) and embodied energy (EE), on the basis that the use of these materials are purely waste diverted from landfill Others attribute only a small embodied energy and carbon to these materials on the understanding that they require some degree of additional processing, storage and handling before they are ready to be sold at the factory-gate. Still others highlight many of these materials can no longer be classified as 'waste-products' [26]. As useful by-products of other industrial processes, there is an argument that it is appropriate to allocate part of the total environmental impact of the primary process to the material and thus to the concrete producer.

Assuming a waste allocation, and considering only the impacts associated with the secondary production of GGBS and SF, the carbon and energy embodied in the constituents of CEM I and hydraulic lime concrete are shown in Table 2.

Table 2 Embodied carbon and embodied energy of constituent materials assuming minimal secondary processing of 'waste' materials [22, 27-28]

CONSTITUENT	EMBODIED CARBON $kgCO_2$/tonne	EMBODIED ENERGY MJ/tonne
CEM I	930	3800
NHL 5	635	2721
GGBS	52	1300
Silica fume	14	500
Water	0.3	10
Aggregates	4	100
Superplasticizer	220	18300

When the data in Table 2 is used to calculate the embodied carbon and energy of a tonne of hydraulic lime-concrete, the results in Table 3 are attained. When comparing the embodied impacts of different binders it is essential to compare them on the basis of a functional unit, in this case compressive strength. The embodied carbon and energy of two other concretes that also attain a 28-day strength of $49N/mm^2$, are shown for comparison. Although the embodied carbon of the lime-concrete is lower than both the CEMI and PC/ggbs (IIIV) cement-concretes, the embodied energy of the lime-concrete is shown to be higher than that of the IIIV concrete. This is because of the lower w/b ratio, or higher overall binder content, required for attaining this strength.

Table 3 Embodied carbon and energy of lime-concrete in comparison to equal strength CEMI and IIIV concretes

BINDER	28 DAY CUBE STRENGTH, N/mm^2	W/B RATIO	EMBODIED CO_2, $kgCO_2$/tonne	EMBODIED ENERGY, MJ/tonne
CEM I	49.0	0.48	135	630
IIIV (50%CEMI/50%GGBS)	49.0	0.40	85	525
50%NHL5, 40%GGBS, 10%SF	49.0	0.35	80	560

Allocation

If considered as ‘waste’ it seems reasonable to consider aluminosilicates, which are produced unintentionally as the result of other industrial processes, as having minimal embodied carbon and energy. However if they are ‘by-products’ or ‘co-products’ it is argued that they must be attributed a certain proportion of the overall impacts of the process. ‘Allocation’ concerns the appropriate determination of these proportions, which are governed by calculation of allocation coefficients

The difficulty policymakers face in standardizing allocation procedures for Life Cycle Assessment (LCA) are that they are seeking to model complex and dynamic real-world systems. As well as substantial regional variations in the industrial production of materials, fluctuating economic markets and incremental changes in production technologies, there are also highly subjective and game changing factors to consider; such as the transition of materials from ‘waste’ to ‘by-product status’.

For example in the 1970’s the use of silica fume in the production of concrete was undisputedly an environmental success. Not only was this waste material no longer an environmental hazard, but its use as a cement replacement was reducing the demand for cement whilst producing stronger and more durable concrete structures. This was, and arguably still is, an ideal example of waste utilization and ‘industrial symbiosis’ [29]. On the other hand some authors argue that the increased demand for silica fume, and the market that emerged for it as a commercial product in its own right, changed the merits of the system. Rather than silica fume being classified as a ‘waste-product’ it might rather be correctly classified as a ‘by-product’, indeed as Van Den Heede and De Belie [26] highlight this alternative classification would be in line with the new European Directive 2008/98/EC [30].

This is more than just a debate about nomenclature, as it affects the way that the environmental impact of the main process is allocated. Allocation is a critical methodological issue in the performance of lifecycle assessments of different materials and systems, particularly in the case of the use of by-products. The effect of the allocation procedure on the end result is so great, that rather than boundaries being drawn to prevent double-counting and negative impacts becoming externalities, they are prone to manipulation in order to produce favourable results for commercially interested parties. Although standard methodologies are clearly needed to prevent manipulation and engender confidence to the results of Life Cycle Assessments, there is considerable controversy about the methodologies to be standardized [31-34]; in particular the allocation of impacts associated with aluminosilicate ‘by-products’ that are used as supplementary cementitious materials by the construction industry [26, 35].

Whilst no standard procedures are in place, an objective assessment of the environmental performance of a new material must take a sensitivity approach, using a number of alternative methodologies to define an environmental impact envelope.

Allocation for GGBS

The effect of two allocation procedures (mass and economic) has been considered by Chen et al. [35], in which it was shown that only economic allocation results in there being beneficial environmental impacts of using GGBS in comparison to CEM I. A mass allocation coefficient (C_m) of 19% and an economic allocation coefficient (C_e) of 2% were calculated for GGBS. The embodied carbon and energy of GGBS, including either mass or economic allocation of the primary production of the steel, are shown in Table 4.

Table 4 EC and EE of GGBS on the basis of mass and economic allocation

	PRIMARY PROCESS (Iron)	SECONDARY PROCESS (GGBS)	TOTAL (Mass Allocation)	TOTAL (Economic Allocation)
Embodied energy, MJ/tonne	25000	1300	6139	1885
Embodied carbon, kg/CO_2 tonne	1900	52	420	96

Allocation for Silica Fume

Being a by-product of two distinct industrial processes, namely the production of silicon metal (>95% Si) and the production of ferrosilicon alloys (<95% Si), both processes need be considered separately. Assuming that global production of ferrosilicon accounts for four-fifths of the total production of silicon-products [1], then the mass allocation coefficients for the production of silica fume from silicon metal and ferrosilicon results in an overall mass coefficient (C_m) of 22%.

A distinct disadvantage of economic allocation procedures is the market price for the primary and secondary products is highly variable in time and space. Minimum allocation coefficients have been calculated for silica fume production based on maximum and minimum spot prices for ferrosilicon (75%), silicon and silica fume in four global markets: US, China, India and Europe. Results are shown in Table 5.

Table 5: EE and EC of silica fume on the basis of mass and economic allocation

	PRIMARY PROCESS (Silicon)	PRIMARY PROCESS (Ferrosilicon)	SECONDARY PROCESS (silica fume)	TOTAL (Mass Allocation)	TOTAL (Economic Allocation)
Embodied energy, MJ/tonne	2355000	2041000	500	460000	70000
Embodied carbon, kg/CO_2 tonne	4500	3900	14	700	120

Effect of Allocation based on EC and EE

Using the data in Tables 2, 4 and 5, four distinct cases have been built for hydraulic lime concrete. The results of this analysis are shown in Figure 1.

(1) GGBS and SF considered to have zero embodied impacts.
(2) GGBS and SF as ‘waste’ in which only impacts associated with secondary processes are considered.
(3) Environmental impacts of SF and GGBS assigned by mass allocation.
(4) Environmental impacts of SF and GGBS assigned by economic allocation.

This exercise demonstrates the pronounced effect of selecting different allocation methodologies in calculating the environmental impacts of cementitious binders including mineral ‘by-products’. Choice of allocation procedure would have a fundamental affect on the selection of the ‘greenest’ binder. Whereas in the case of GGBS it has been shown that economic allocation procedures maintain environmental benefits in comparison to CEMI, both mass and economic allocation procedures have a detrimental affect on the environmental credentials of silica fume, particularly pronounced in the case of embodied energy because of the extremely energy intensive manufacture of silicon.

A CASE STUDY

Amidst discussion of the global backdrop in the search for new low carbon-cements and the controversy over the classification and impact of supplementary cementitious materials, it is easy to forget the scale and nature of the dialogue about the hydraulic lime-concrete presented. The hydraulic lime-concrete discussed in this paper was not developed as successor, or wide scale alternative, to CEMI but rather was investigated to understand the feasibility and appropriateness of this as a sustainable solution for two specific projects in the UK. The laboratory testing that has been undertaken to date, and the assessment of the comparative impact of this material, has been undertaken in order to try and meet project-specific aspirations. Given the local and temporal variability of environmental impact assessment, there was a strong case for considering the environmental impact of lime-concrete at a project scale.

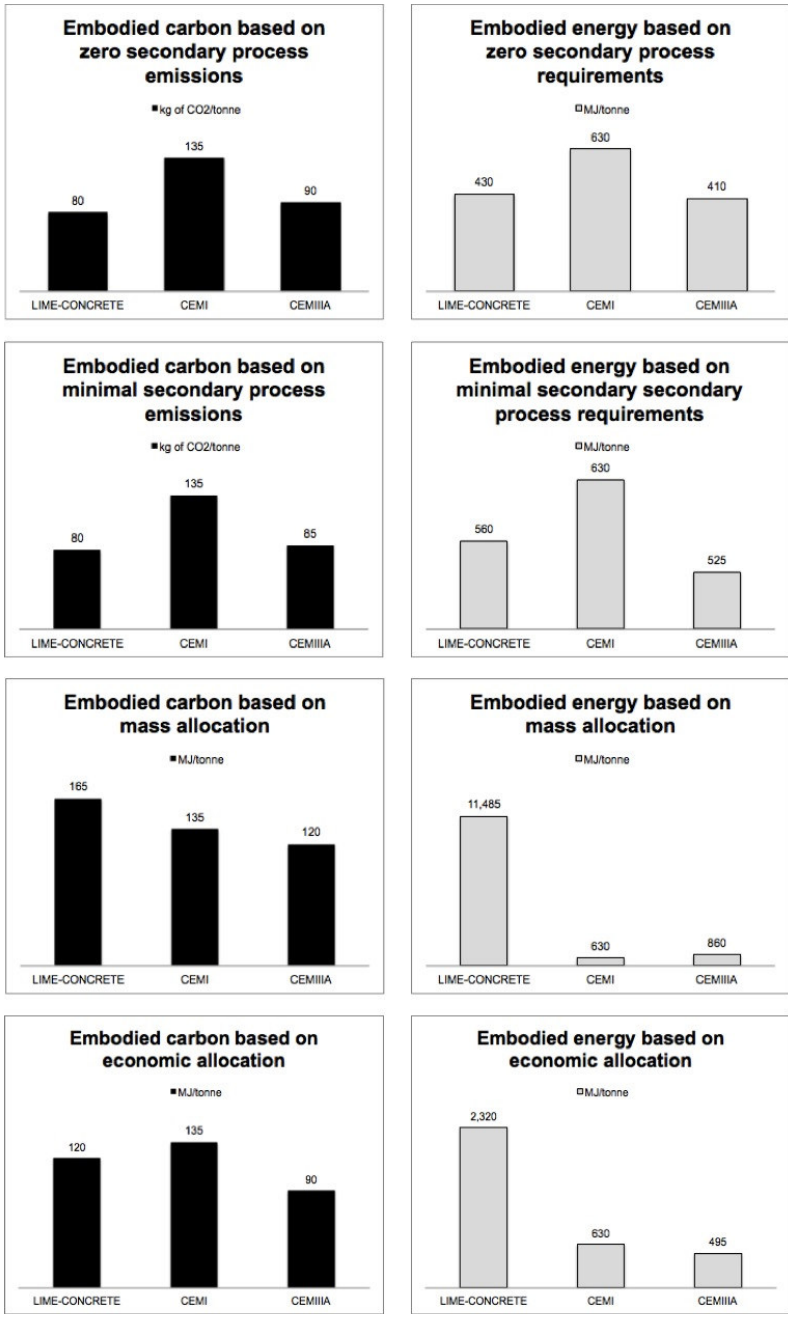

Figure 1: Effect of four different allocation procedures on the EE and EC of three equal strength concretes

After twelve months of design development in conjunction with laboratory testing, a lime-concrete floor screed was specified for the ground floor of a school building in the UK. This use facilitated the use of lime whilst also displaying the aesthetic of the naturally weathered limestone aggregate available on the school site. The embodied energy and carbon of the polished lime-concrete floor slab is compared with that of a typical vinyl floor, which is considered to be a conventional solution for this school application, in Table 6. Although, not a full comparative LCA of these two flooring solutions, which would be beyond the scope of this paper, this simplified analysis is however included to demonstrate approximate energy and carbon savings associated with the choice of flooring system and specifically, in the case of the two alternative polished floor options, the effect of the choice of binder.

It can be seen from Table 6 that the polished lime-concrete option had the lowest embodied carbon and energy of the three flooring options. A polished CEMI concrete floor had a lower embodied energy but a higher embodied carbon than a vinyl option. In the case of the polished concrete floor options it is worth noting that the steel reinforcing mesh accounts for a large proportion of the total embodied energy of the overall system. The carbon emissions associated with transporting hydraulic lime across Europe have been shown to be minimal (around 40kgCO_2/t of lime) in comparison to those associated with the manufacture of the binder (635kgCO_2/t of lime). The additional transport impacts cannot therefore be used as a legitimate argument for choosing to use a locally available CEMI alternative.

Table 14 EC and EE comparison of three alternative school floor options

	THICKNESS, mm	EMBODIED ENERGY, MJ/m^2	EMBODIED CO_2, kgCO_2/m^2
CONVENTIONAL FLOOR			
Sand-cement screed	65	143	25
Self-levelling screed	3	7	1
Epoxide resin adhesive	-	63	3
Vinyl	2.5	197	7
Sum =	**70.5**	**410**	**36**
TYPICAL POLISHED CONCRETE FLOOR			
CEM I concrete	100	151	32
Reinforcing mesh + spacers	-	112	8
Polishing	-	65	9
Sum =	**100**	**328**	**49**
TYPICAL POLISHED HYDRAULIC CONCRETE LIME FLOOR			
Hydraulic lime concrete	100	81	10
Reinforcing mesh + spacers		112	8
Polishing		65	9
Sum =	**100**	**258**	**27**

CONCLUDING REMARKS

The hydraulic-lime binder presented in this paper is an incremental innovation in the evolution of cementitious materials. Alternative technologies being developed concurrently with this one are arguably more radical innovations in the field of cement technology. Although a radical technological solution will in the long-term realize greater environmental benefits, in the intervening period, lime-pozzolan based concretes could meet the imminent demand for a lower-environmental alternatives to CEMI concretes. The incremental nature of this innovation, combined with the historical precedent for the use of lime in construction, is undoubtedly a real advantage for this solution in terms of market entry. In the case of this binder, technological similarities with CEMI, such as being manufactured by the calcination of limestone and the potential to be blended and bagged as a dehydrated mixture to which water can just be added, are seen as advantage in the short-term and disadvantages in the long-term.

The combination of aluminosilicate additions, which have been investigated in this research may be deemed appropriate for the UK construction industry, but are unlikely to be the only, or the most appropriate, combination in other regional markets. For example in India where the price of silica fume is high, it may be that rice husk ash, has the potential to facilitate a similar pozzolanic reaction. Based on the promising results of laboratory testing, there is substantial scope for broadening this field of enquiry into the testing and development of regional blends. Although the impacts associated with the transportation of hydraulic lime have been shown to be low in comparison to its production, it is clear that there are social, environmental and economic benefits to the production of regional lime-pozzolan concretes that exploit locally available materials.

Comparison of the embodied carbon of this material, with a IIIV cement, raises questions as to the magnitude of the environmental benefits of this ‘cement-free’ solution. However there are other potential material property differences that might prove advantageous in specific applications. For example further work is needed to quantify differences in elastic modulus, compatibility with other materials, compatibility with historic structures and the breathability of this material. With an environmental impact on a par with the current best practice for the specification of sustainable concretes, further research is necessary to establish other potentially advantageous properties of lime-concretes to support their uptake.

Particularly in the case of silica fume, it can be seen that the classification of aluminosilicates as ‘by-products’ could have devastating implications on their inclusion in ‘green’ concretes. It is important that issues of nomenclature do not unintentionally undermine the sensible and sustainable closed-loop utilization of materials. Rather interoperable systems that promote the flow of materials and prevent waste must be protected and designed. Two extreme scenarios can be imagined that would indicate failure of the overall system. Clearly the system would have failed if the use of these materials was abandoned by the cement industry and these materials tended once again towards ‘waste’. Equally the production of silicon metal as a by-product of the industrial production of aluminosilicates for ‘green’ cement manufacture is clearly an example of high-level system failure. Although these scenarios represent extreme cases, they do highlight the consideration that needs to be given to the regulation of allocation procedures.

Overall a ‘systems thinking’ approach to the development of second-generation cements is needed, which requires in depth consideration of the cost-feasibility, production-feasibility, long-term feasibility and comparative performance of different cement blends. Such an approach will require increased collaboration between academia and industry. A collaborative cross industry approach is needed to guide research and evaluate the sustainability of potential innovative cementitious systems.

ACKNOWLEDGMENTS

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8.6 PAPER 7: The environmental credentials of hydraulic lime-pozzolan concretes

Ellen R Grist[a,b], Kevin A Paine[b], Andrew Heath[b], James Norman[c], Henry Pinder[a]
a. Ramboll, 40 Queen Square, Bristol, BS1 4QP, UK
b. University of Bath, Claverton Down, Bath, BA2 7AY, UK
c. University of Bristol, Bristol, BS8 1TR, UK

Abstract

Against the backdrop of the hunt for Low Carbon Concretes (LCCs) this paper considers the environmental credentials of lime-pozzolan concretes in comparison to Portland-cement based concretes. Specifically, this paper discusses the compressive strength, embodied CO_2, embodied energy and binder intensity of a range of novel lime-pozzolan concretes.

Whilst previous studies had demonstrated that a ternary combination of natural hydraulic lime (NHL5), ground granulated blastfurnace slag (GGBS) and silica fume (SF) could result in a concrete with a 28-day cube strength of approximately 50MPa and an elastic modulus of 20GPa, the question remained as to whether this was desirable alternative solution?

This paper demonstrates that the use of GGBS and SF, in combination with NHL5 can realise savings in environmental energy and CO_2, but that the potential savings are highly dependent on the boundaries of the analysis, specifically the choice of allocation procedure used to quantify the impact of the GGBS and SF.

Consideration also has to be given to the long-term feasibility and desirability of re-producing these novel cementitious systems in a commercial setting.

Keywords: *Sustainability, hydraulic lime-pozzolan concrete, binder intensity, embodied CO_2, embodied energy*

Introduction

In 2012 over 3.7 billion tonnes of cement were produced worldwide (Van Oss, 2013) enough to produce over 12 billion m^3 of concrete or 1.7 m^3 for every man, woman and child on the planet. As the principal binding constituent of concrete, cement continues to be a key driving force of human development.

The manufacture of Portland cement (CEM I) is a carbon and energy intensive process and is widely acknowledged to be responsible for 5-9% of the total global anthropogenic carbon dioxide emissions (Metz, 2007, Shi et al., 2011, Harrison, 2013) and 2-3% of primary energy use (Juenger et al., 2010). The actual energy demand and energy related emissions vary significantly between production facilities, due to differing processing technology and national energy generation strategies. Japan pioneers energy-efficiency in cement kiln technology and boasts dry-process kilns with suspension pre-heaters and pre-calciners requiring less than 3000 MJ/t clinker (Japanese Cement Association, 2011a). This is less than half the heat requirement of the older wet-kiln technology that demand up to 6300 MJ/t (Boesch and Hellweg, 2010).

Despite pressure to reduce its environmental impact, the global cement industry must continue to invest in capacity expansion programmes in order to meet the growing demand. Investment in modern production technologies both minimizes the environmental impact and maximizes profitability for the cement producer. However with an upper limit on the overall kiln efficiency, the returns associated with the investment in the best available technologies (BAT's) are diminishing. Production efficiency is therefore not the only strategy for reducing the impact of cement manufacture on the natural environment. Other strategies include alternative fuel sources, carbon-capture and storage and the development of alternative cements (International Energy Agency, 2009).

The aim of this study has been to investigate the embodied CO_2 (EC) and embodied energy (EE) of modern lime-pozzolan cements, as well as to evaluate the viability of this 'novel' cementitious system. This paper starts with detailed introduction to this alternative binder technology and its constituents, in order to contextualise the findings of this research.

Alternative cements

One of CEM I's greatest advantages as a cement has been the widespread availability of raw materials for global production and the wide scale applicability of the material in use. With no other single cement technology set to replace it, a shift in product mix is anticipated with a number of ‘second generation’, ‘low-carbon’ cements being developed (Gartner, 2009). Potential second-generation cements that are in different stages of research and development include: calcium sulfoaluminate cements (CSAC) (Ioannou et al., 2014), supersulfated cements (SCC) (Ioannou et al., 2013), alkali activated cements (AAC) and geopolymers (Heath et al., 2013), magnesium oxide cements (Liska et al., 2012), high volume slag cements (Saleh et al., 2012) and ternary cements (De Weerdt et al., 2011), as well as hydraulic lime-pozzolan cements (Grist et al., 2013a).

With a total installed capacity of 3.2 billion tonnes of clinker (Van Oss, 2013) and modern concrete construction practice entirely geared to the production and use of Portland cement, novel cements face a very difficult route to market. It is however appreciable that it is the compressive strength, durability and ease of placement of concrete that is so fundamental to construction and not the nature of the cementitious binder itself.

Rising fuel costs, carbon reduction targets and a growing demand for more sustainable alternatives are driving change and forward-thinking cement manufacturers are preparing to respond with new product technologies. Commenting on emerging low carbon cements, Chana (2010) argued, *“there is a future for new or novel cements…but there really is a long way to go before they can make substantial inroads into the market”* (Mineral Products Association, 2010). To envisage the ‘post-Portland cement age’ material scientists, contractors and consumers alike, need the ability to make sense of the benefits of alternative technological solutions. Against this backdrop this paper specifically reflects on the sustainability credentials of lime-pozzolan cements as an alternative to CEM I based cements.

Hydraulic-lime concrete

Lime-pozzolan binders have a long history; a lime-concrete floor slab discovered in Southern Israel in 1985 was dated back to 7000BC (Bensted and Coleman, 2003). However, the research reported in this paper does not represent a return to a former technology, as it exploits carefully produced and controlled pozzolanic materials and takes advantage of significant modern advances in the development of concrete technology, specifically the performance of the latest generation of water reducing admixtures. That said, the considerable precedence for the use of this binder in construction is a significant advantage in comparison to other novel cements; therefore its long history, which is a testament to the durability of this material, should not be disregarded.

In the 1770's the civil engineer John Smeaton conducted extensive testing on lime-pozzolan concretes in a search for a suitable hydraulic concrete for construction of the foundations of the third Eddystone Lighthouse off the coast of Plymouth, UK. The mix Smeaton specified for this project consisted of blue lias slaked lime, pozzolanic trass and some copper slag (Bensted and Coleman, 2003). More recently Cachim et al. (2010) attained a 28-day cube strength of 17 MPa with 20% of the hydraulic lime replaced with metakaolin, a synthetic pozzolan.

The hydraulic lime-pozzolan concretes discussed in this paper should not be confused with 'Limecrete' a commercially available lime-concrete suitable for low-grade structural applications. Rather the concretes presented in this paper have a 28-day compressive strength of up to 50 MPa and can be cast into reinforced elements with a similar finished appearance and structural behaviour to Portland-cement concrete elements (Grist et al., 2013c).

Hydraulic lime production

Until the advent of Portland-cement (CEM I) in the 1800's, hydraulic lime was the principal binder for use in construction (Kenny and Oates, 2000). Both hydraulic lime and CEM I are synthetic materials manufactured by the thermal decomposition of a source of calcium carbonate (typically limestone) at high temperatures. At kiln temperatures in excess of 900°C calcium carbonate ($CaCO_3$) disassociates, with carbon dioxide (CO_2) being driven off to produce calcium oxide (CaO), commonly known as quicklime. The hydraulic set of both hydraulic lime and CEM I results from the presence of active calcium silicates phases, which are formed in the reaction of quicklime (CaO) with silica, alumina or iron oxide. These minerals are either added to the raw feed as a controlled blend of clay impurities in the case of CEM I and hydraulic lime; or are inherent in the original siliceous or argillaceous limestone deposit in the case of natural hydraulic lime (NHL).

Different calcium silicate phases form at different kiln temperatures and in different parts of the kiln. CEM I typically includes four primary calcium silicate minerals of which alite (Ca_3SiO_5) is the most predominant. Alite forms at kiln temperatures of above 1300°C and is responsible for the rapid set of CEM I. Eminently hydraulic lime (NHL5) by comparison contains only a trace amount of alite (<0.7%) and the dominant compound (43%) is belite (Ca_2SiO_4), which forms at 900°C (CESA, 2006b). The mineralogical composition of NHL5 is shown alongside a typical CEM I (Dhir et al., 2001) in Table 1

Table 18: Mineralogical composition of NHL5 in comparison to CEM I

Compounds	Typical NHL5, % by mass	Typical CEMI, % by mass
Insoluble content	4	trace
Free lime, $Ca(OH)_2$	21	2
Unburnt calcium carbonate, $CaCO_3$	23	0
Alite, Ca_3SiO_5	trace	58
Belite, $(CaO)_2.SiO_2$	45	13
Tricalcium aluminate, $3CaO.Al_2O_3$	2	9
Gehlenite, $Ca_2Al(AlSiO_7)$	2	0
Calcium aluminoferrite, $Ca_2(Al,Fe)_2O_5$	2	8
Gypsum, $CaSO_4$	trace	5
Other	1	5

Carbon and energy savings associated with the production of NHL, as opposed to CEM I, are evident when one compares the stoichiometric reactions describing the production of alite and belite (see equations 1.1 and 1.2).

Production of alite

$$\underset{300.3}{3\ CaCO_3} + \underset{60.1}{1\ SiO_2} \xrightarrow{\sim 1400°C} \underset{228.3}{1\ Ca_3SiO_5} + \underset{132.0}{3\ CO_2} \qquad \textit{Equation 1.1}$$

Production of belite

$$\underset{200.2}{2\ CaCO_3} + \underset{60.1}{1\ SiO_2} \xrightarrow{\sim 900°C} \underset{172.3}{1\ (CaO)_2SiO_2} + \underset{88.0}{2\ CO_2} \qquad \textit{Equation 1.2}$$

Expressed in terms of mass, every tonne of alite produced liberates 579 kg of CO_2, whereas every tonne of belite produced liberates 511 kg of CO_2. This suggests a potential 12% saving in the raw-material CO_2 (RM-CO_2). In addition, there is CO_2 produced from the heat generation; but this 'fuel-derived' CO_2 (FD-CO_2) is dependent on the efficiency of the kiln and type of fuel used. Since belite forms at a lower kiln temperature than alite, further energy and carbon savings result from reduced kiln temperatures that require less fuel. The vertical-shaft kilns used for production of NHL5 tend to operate at 1000°C (CESA, 2006b). This is substantially lower than the 1450°C which is needed for the calcination of limestone to produce the alite in CEM I; although some of the additional energy needed for the extra temperature may be recovered in the form of preheated air for fuel combustion (Bye, 2011). Equations 1 & 2 also demonstrate the raw-material savings. One tonne of calcium carbonate, appropriately clinkered with silica, yields 860 kg of belite or 750 kg of alite.

Disintegration of the sintered lumps of quicklime during slaking substantially reduces the demand for finish grinding of NHL in comparison to CEM I, with only 25% of the slaked lime coming out of the hydrator requiring further grinding to achieve a particle size of 0.09 mm (CESA, 2006b). In Europe the total electricity consumption per tonne of CEM I is reported to be between 90-120 kWh, of which around 40% of this total (36-48 kWh) is required for grinding the clinker (Boesch and Hellweg, 2010).

The savings associated with the production of lime are discussed here as latent savings as it is recognized that this smaller scale industry has not had the level of investment in production technology as the cement industry has and therefore is unlikely to be operating at the same kiln efficiencies. That said, given that the production of lime, like cement, is based on the calcination of limestone, it is suggested that similar or improved kiln efficiencies are possible in this industry.

Aluminosilicate mineral additions

Although there are a number of aluminosilicate materials that can be used in lime-pozzolan concrete mixes, the use of ground granulated blastfurnace slag and silica fume have been determined to be the most promising in initial studies (Grist et al., 2013a). These synthetic materials are both by-products of current industrial processes.

Ground Granulated Blastfurnace Slag (GGBS)

GGBS is a latent-hydraulic Type II addition, permitted to replace CEM I by up to 80% by mass in structural concreting applications in Europe (BS EN 197-1, 2011) and by up to 95% by mass in concretes specified for maximum strength, such as secant piles. It is sold as a high quality, environmentally friendly material that improves many aspects of performance and reduces the EC of concrete (Mineral Products Association, 2011b).

GGBS is a by-product of the reduction of iron ore to produce metallurgical iron. Iron is manufactured by reduction of the ore, in the presence of carbon, in a blastfurnace at 1500°C. Molten slag, which consists of the impurities in the ore and other ‘slagging’ agents, floats on the surface of the molten iron and both layers are regularly tapped out of the furnace. The molten slag that is to be processed for production of GGBS is rapidly quenched, by pouring it into a jet of cold water, to produce an amorphous granular material similar to coarse sand. This is then dried and ground to a similar fineness to cement.

In 2011 total global production of blastfurnace slag exceeded 770 Mt (based on a typical ratio of 0.28 t of slag to every t of crude iron produced) (Van Oss, 2012). Not all of this blastfurnace slag was suitable for granulation and grinding, and only 200 Mt (26%) was sold as GGBS. Hypothetically even if all global blastfurnace slag could be sold as GGBS for cement replacement, it would still amount to less than 25% of the total mass of CEM I produced per annum. Although it is difficult to determine the extent to which physical and economic factors will limit future production levels, it is clear that cementitious systems based on high replacement levels of GGBS will not be able to meet the total global requirement for sustainable binders. It is evident that in the development of low carbon cements a diversification of raw material utilization is essential.

The Mineral Products Association reports that GGBS has an EC of 52 $kgCO_2/t$ (Mineral Products Association, 2011b). This figure includes the carbon dioxide associated with the secondary processes, namely granulation of the slag, transport to the slag grinding plant and carbon dioxide derived from drying and grinding. An EE of 1300 MJ is reported to include the production and distribution of electricity associated with these processes. It has been argued that the impacts of the iron-making should not be taken into account because the slag evolves, irrespective of whether or not it is used (Higgins, 2007). Whilst it is agreed that the evolution of slag is inevitable, as the market for GGBS has grown the probability of this increasingly high-value product not being utilized has fallen, and thus the validity of this approach can be challenged. As a consequence a number of authors (Chen et al., 2010, Van den Heede and De Belie, 2012) have questioned whether some of the environmental impact of iron production should be assigned to the slag and thus allocated to the concrete producer.

There are five slag grinding plants in the UK and it is estimated that a third of all UK ready-mix concrete deliveries include GGBS (Jones, 2011). In the UK the most commonly used blastfurnace cement has a GGBS content of 50% by mass, designated CEM III/A; this has been calculated to result in a 40% reduction in CO_2 emissions and a 30% reduction in primary energy, in comparison to CEM I concrete (Higgins, 2007).

Silica fume (SF)

SF consists of spherical particles of amorphous silicon dioxide, SiO_2. SF forms during the production of metallurgical grade silicon and ferrosilicon alloys. In both industrial processes quartz (a crystalline form of SiO_2) is reduced with a source of carbon (typically coal, coke or charcoal) in electric arc furnaces at temperatures in excess of 2000°C. One of the reduction reactions produces volatile silicon monoxide vapour, which is ejected from the stack. Oxidation of the silicon monoxide, at the top of the stack, produces silicon dioxide, which condenses into extremely fine ‘smoke’ particles of SF (Silica Fume Association, 2005).

SF is a highly-reactive pozzolanic material, which improves both the rheology of fresh concrete and the strength and durability of the hardened material. Appreciation of the benefits of the use of SF as a supplementary cementitious material in the production of high strength concrete has seen the transition of this material from a polluting waste-product to a valuable high-performance concrete addition (Fidjestol and Magne, 2008). Such is the market demand for SF today that plants run to produce SF during a down-turn in alloy sales. Indeed high-purity, refractory grade SF is routinely produced with silicon-metal as a by-product (Myhre, 1996).

The suitability of industrial by-products as constituents of low carbon cements is questioned by those concerned about the long-term security of supply, which is governed by the longevity of the primary industry. The raw material for the production of silicon, quartz or quartzite, is abundantly available. As a by-product of the silicon metal and ferrosilicon alloy industries, the future availability of SF can reasonably be assessed by the projected demand for these two materials. Although novel materials such as graphene might in time impact silicon production in the consumer electronics market, the production of silicon metal and ferrosilicon alloys is principally driven by metal foundry industries, with ferrosilicon being a critical alloying component of iron in the production of steel (Holappa, 2010) and silicon used similarly in the production of aluminium alloys. The graph in Figure 27 shows the strong growth of global silicon production in the last fifteen years.

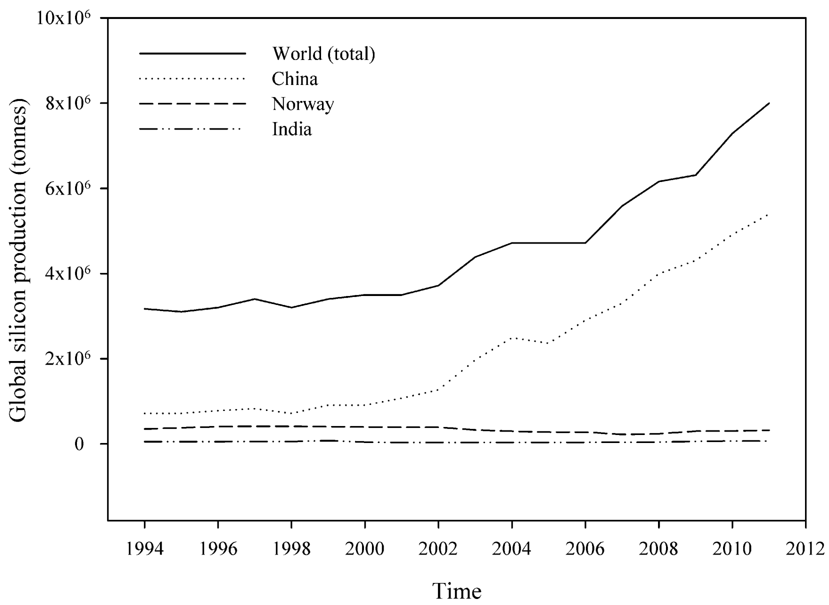


Figure 27: Trends in global silicon production (USGS, 2012)

Long-term security of supply of industrial by-products

It is worth noting that continued production is not the only determinate of availability of SF and GGBS for use as supplementary cementitious additions. As Van Oss (2012) highlights, Environmental Protection Agencies, and other bodies involved in the classification of materials, wield significant influence over the market. Hypothetically if any, or all, of these materials were ever to be designated as 'hazardous wastes' for example, demand for one, or more, might fall dramatically as a result of stigmatization. This could threaten sales regardless of whether or not scientific evidence is able to demonstrate the safe stabilisation of these materials in concrete (Chen et al., 2009). The desire to utilise waste materials in concrete varies between national markets due to variable availability and status (Togerö, 2006). Such potential risks are a good argument for developing cementitious systems based on geological resources, such as naturally occurring pozzolanic materials. Further research should be done to look at the potential substitution of GGBS for naturally occurring pozzolanic materials such as regional volcanic ashes.

A carbon foot-printing exercise commissioned by a silicon manufacturer and performed by a third party consultancy reports an EC of 14 kgCO_2/t of SF slurry (Enviros Consulting, 2009). This figure includes collection and secondary processing of the SF as well as transportation of the slurry to the UK. The EC associated with the industrial production of SF in Norway is low due to the country's hydroelectric power generation. An EE figure of 18 MJ/t is reported for SF produced in Norway (ELKEM, 2013). This figure includes the energy associated with processing, packaging and storing SF until it leaves the factory gate. It does not include collection of the SF, which has been a legal obligation in Norway since 1974 when legislation was introduced to reduce air pollution (Myhre, 1996).

Calculation of embodied CO_2 and energy

When calculating the EC and EE of blended cements incorporating supplementary cementitious materials that are by-products of other industrial processes, great care has to be taken in the collection and allocation of the data (Ekvall and Finnveden, 2001).

It is a relatively common practice in environmental impact studies to classify these materials as 'waste products' and thus attribute them with zero EC and EE, on the basis that these emissions arise, whether or not the materials are then diverted from landfill for use (Habert and Roussel, 2009, Damineli et al., 2010). Others attribute only a small EC and EE to these materials on the basis that they require some degree of additional secondary processing, storage and handling before they are ready to be sold at the factory-gate (Kawai et al., 2005, Flower and Sanjayan, 2007). Still others highlight that these materials can no longer be classified as 'waste-products' (Habert and Roussel, 2009, Van den Heede and De Belie, 2012). As useful by-products of other industrial processes, there is an argument that it is appropriate to allocate part of the total environmental impact of the primary process to the material and thus to the concrete producer (Chen et al., 2010, Van den Heede and De Belie, 2012, Habert, 2013).

This is more than just a debate about nomenclature, as it affects the way that the environmental impact of the main process is allocated. Since 2008 GGBS and SF having been officially classified as 'by-products' in line with a new European Directive 2008/98/EC (European Union, 2008), but to date no allocation procedure has been decided upon. The effects of a number of different allocation procedures have been being considered by policy makers in an attempt to rule out procedures that would unfairly disadvantage the different industries. The two allocation procedures that were considered in this study were mass allocation and economic allocation.

Methodology

Goal of the study

Recent research considering the properties of a range of binary and ternary lime-pozzolan binders has demonstrated that the pozzolanic reaction, resulting from the inclusion of alumina-siliceous additions, substantially enhances the compressive strength of resultant mortars or concretes (Grist et al., 2013a). Such additions not only improve the material properties but also are a determinate of its environmental impact. A detailed life-cycle assessment of all the constituent components of this innovative composite material is beyond the scope of this paper as these are specific to the mix design, location and intended use. Rather, this paper offers the reader an opportunity to step back and consider the bigger picture, facilitating a high-level comparison of the relative environmental impacts and potential savings that create opportunities for further development of this novel concrete technology.

The investigation into the environmental impact of lime-pozzolan concretes comprised two studies. The first study compared the EC and EE of lime-pozzolan concretes produced in the laboratory, with two reference CEM I-based concretes of equivalent strength. The second study explored the sensitivity of the environmental impact analysis to methodological choices.

Embodied CO_2 and energy comparison

In this study the embodied impacts of four alternative hydraulic lime-pozzolan concretes were calculated. The lime-pozzolan binders investigated in this study were all ternary combinations of NHL5, GGBS and SF. The embodied impact of an NHL5-only concrete was also calculated for comparison.

Given that GGBS has a substantially lower environmental impact than NHL5 (considering secondary processing impacts only), it was decided to investigate how varying the ratio of NHL5 to GGBS affected the strength, and thus also the binder efficiency, of the resulting ternary lime-pozzolan concretes. The addition of SF was fixed at 12% of the total binder content in each case, based on previous findings (Grist et al., 2013c). Each of the three ternary NHL5-GGBS-SF concretes had a total binder content of 465kg/m^3 and a water to binder (w/b) ratio of 0.42. They were designated concretes (I) – (III):

- 53% NHL5, 35% GGBS and 12% SF (I)
- 38% NHL5, 50% GGBS and 12% SF (II)
- 23% NHL5, 65% GGBS and 12% SF (III)

In order to investigate the effect of the total binder content on the eco-efficiency of the resulting lime-pozzolan concrete, one further NHL5-GGBS-SF concrete was also analysed in this study. This lime-pozzolan concrete, produced in a previous study (Grist et al., 2013c), had an overall binder content of 546kg/m^3 and a w/b ratio of 0.35. This concrete had a 28 day compressive strength of 49MPa and is designated concrete (IV).

- 50% NHL5, 40% GGBS and 10% SF (IV)

A control mix of 100% NHL5, designated mix (0), was also produced to establish the contribution of the pozzolanic reaction to compressive strength.

Two CEM-based concretes were also analysed in this study to provide a frame of reference when interpreting the results. Specifically, comparable CEM I and CEM III/A (50% CEM I & 50% CEM III/A) concretes were extrapolated from the work of Dhir et al. (2001) as a basis for comparison. 28-day cube strength was selected as the unit of functional performance when comparing the environmental impact of the alternative concretes. The requirement to compare concretes of the exact same 28-day strength meant that comparable concretes were typically hypothetical based on extrapolated material properties as opposed to empirical test results.

When calculating the EC and EE of the concretes, only the impacts associated with the secondary processing of the aluminosilicate additions, GGBS and SF, were assumed. EC and EE data for all the constituents of the lime-pozzolan and CEM I-based concretes is shown in Table 19.

Table 19: EC and EE of constituent materials assuming minimal secondary processing of 'waste' materials

Data sources: CESA, 2006a, European Federation of Concrete Admixture, 2006, Enviros Consulting, 2009, Mineral Product Association, 2011b, ELKEM, 2013

	Embodied CO_2	Embodied energy
	$kgCO_2/t$	MJ/t
CEMI	930	3,800
NHL5	635	2,721
GGBS	52	1,300
SF	14	18
Water	0.3	10
Aggregate	4	100
Superplasticiser	220	18,300

Using this data the EC and EE of all the concretes was calculated and compared, as were the carbon and energy intensity indices in accordance with the work of Damineli et al. (2010).

Materials

To produce concretes comparable with concrete (IV), the constituent materials and procedures for proportioning the aggregates, specimen production and curing, were all identical to those employed in the earlier work (Grist et al., 2013c). An NHL5 conforming to BS EN 459-1 (2010) was used. The SF was obtained in the form of a slurry, with a SF:water ratio of 50:50 by mass, and conformed to BS EN 13263-1 (2005). The GGBS conformed to BS EN 15167-1 (2006).

The mix design process for concrete described by Teychenné et al. (1997) was used as the basis for proportioning aggregates. The coarse aggregate comprised a 5-10 mm and 10-20 mm carboniferous limestone. The fine aggregate was 50% Marlborough grit and 50% fine building sand by mass. The particle size distributions (PSDs) of all the aggregates were determined in accordance with BS 933-1 (2012) and are shown in Table 20.

Table 20: PSD of aggregates

Seive size (mm)	% passing Coarse aggregate	Fine aggregate	Marlborough grit	Building sand
40	100	100	100	100
28	100	100	93	100
20	87	100	54	99
14	25	100	38	96
10	1	87	17	93
6.3	0	22	0	82
4	0	0	0	10
2	0	0	0	1
1	0	0	0	0

The mix constituents of each of the concretes are given in Table 21.

Table 21: Concrete mix constituents

Mix description	Free water content	Total binder content	w/b ratio	CEMI	NHL5	GGBS	SF	Coarse aggregate	Fine aggregate	SP
	kg/m^3	*kg/m^3*		*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*
Lime-pozzolan concretes:										
(0)	197	465	*0.42*	0	465	0	0	930	770	4.8
(I)	197	465	*0.42*	0	246	163	56	930	775	4.0
(II)	197	465	*0.42*	0	177	233	56	930	780	3.7
(III)	197	465	*0.42*	0	107	302	56	930	785	3.5
(IV)	190	546	*0.35*	0	273	218	55	885	750	6.5
CEMI reference concretes:										
CEMI (49 MPa)	175	365	*0.48*	365	0	0	0	1315	515	0
CEMI (33 MPa)	175	273	*0.64*	273	0	0	0	1295	640	0
CEMI (13 MPa)	175	175	*1.00*	175	0	0	0	1260	920	0
CEMIII/A (49 MPa)	175	461	*0.38*	230	0	230	0	1315	450	0
CEMIII/A (33 MPa)	175	307	*0.57*	154	0	154	0	1315	575	0
CEMIII/A (13 MPa)	175	213	*0.82*	107	0	107	0	1285	735	0

The lime-pozzolan concretes were prepared in a rotary pan mixer according to the standard procedure detailed in BS EN 1881-125 (2013). Each concrete was dosed with the minimal quantity of polycarboxylate ether (PCE) superplasticiser (see Table 21) to produce concretes of equal consistence. Concretes were cured under polythene sheeting for 24-hours and then in a conditioning lab maintained at 20±0.5°C and 60-65% RH, in accordance with BS EN 12390-2 (2009), until testing.

The compressive strength of concretes (0-III) was measured in accordance with BS EN 12390-3 (2009) at 2, 7, 28 and 56 days. The static modulus of elasticity in compression of the lime-pozzolan concretes was also determined in accordance with the method described in BS EN 1881-121 (1983) at 28-days.

Sensitivity analysis

The analysis used in the first study assumed only minimal EC and EE values when quantifying impacts associated with the production of the GGBS and SF. In this study mass and economic allocation methodologies have been used to define an environmental impact envelope for lime-pozzolan concretes. Mass-allocation proportions, and allocates, the overall production impacts based on the ratio of the mass of the primary product to the mass of the by-product, whereas economic-allocation is based on the market value of primary and by-product respectively. A mass allocation coefficient (C_m) of 19% and an economic allocation coefficient (C_e) of 2% were adopted for GGBS in this study as reported by Chen et al. (2010). Furthermore the methodology for deriving these coefficients was used to calculate the equivalent coefficients SF.

Calculation

GGBS

The embodied impact of the co-product ($\vec{F}_{co-product/waste}$) has been calculated using Equation 2.1, in which $\vec{F}_{primary\ process}$ is the impact of manufacturing the primary product and $\vec{F}_{secondary\ process}$ the additional impact associated with the secondary processing (for example collecting, drying, grinding) of the co-product. The allocation coefficient, determined by the choice of methodology, is denoted C.

$$\vec{\mathbf{F}}_{\mathbf{co-product/waste}} = \mathbf{C}.\vec{\mathbf{F}}_{\mathbf{primary\ process}} + \vec{\mathbf{F}}_{\mathbf{secondary\ process}} \qquad \textit{Equation 2.1}$$

In this analysis, $\vec{F}_{primary\ process}$ has been assumed to equal the EC, or EE, of virgin iron production as reported by Hammond and Jones (2009). The EC and EE of GGBS, including either mass or economic allocation of the primary production of the steel, are shown in Table 22.

Table 22: EC and EE of GGBS on the basis of mass and economic allocation

	Units	Primary Process (Iron)	Secondary Process (GGBS)	Total (mass allocation)	Total (economic allocation)
Embodied energy	MJ/t	25,000	1,300	6,139	1,885
Embodied CO_2	$kgCO_2/t$	1,900	52	420	96

Silica Fume

As SF is a by-product of two distinct industrial processes, namely the production of silicon metal (>95% Si) and the production of ferrosilicon alloys (<95% Si), both industrial processes need to be considered separately. Typical masses of silica fume arising from silicon and ferrosilicon production are reported in Table 6 (Fidjestol and Magne, 2008). Table 23 also shows the mass allocation coefficients (C_m) for the two processes, which were calculated using Equation 2.2 as described by (Chen et al., 2010).

$$\mathbf{C_m} = \frac{\mathbf{m_{by-product}}}{\mathbf{m_{main\ product} + m_{by-product}}} \qquad \textit{Equation 2.2}$$

Table 23: Mass allocation coefficients for Si and SiFe75%

Product	Typical mass produced (kg)	Allocation by mass, C_m
Silicon	1000	69%
SF	450	31%
Ferrosilicon[1]	1000	82%
SF	225	18%

1. Considering the production of FeSi75%

Assuming that ferrosilicon production accounts for 80% of the total global production of silicon-metal products (on a gross-weight basis) (USGS, 2012), then the mass allocation coefficients for the production of silica fume from silicon metal and ferrosilicon results in an overall weighted mass coefficient (C_m) of 21%.

A notable disadvantage of economic allocation procedures is that the market price for the primary and secondary products is highly variable between regions and over time. Minimum allocation coefficients have been calculated for silica fume production based on maximum and minimum annual spot prices for ferrosilicon (75%), silicon metal and silica fume in four global markets: US, China, India and Europe (see Table 24). Results are shown in Table 26. Global prices were converted into Euros/t (€/t) according to the currency conversion rates shown in Table 25.

Table 24: Maximum and minimum dealer import prices for Fe, FeSi75% and SF (2010) based on monthly averages from Platts Metals Week

Market	Si (>95%)		FeSi75%		Silica Fume	
	Min price	Max price	Min price	Max price	Min price	Max price
	€/t	€/t	€/t	€/t	€/t	€/t
India	1345	1681	840	1050	*320*	400
US	2109	2460	1511	1634	240	320
China	1260	1512	781	819	120	*240*
Europe	1800	2100	1120	1250	240	320

Due to a lack of data, the price of silicon in India was estimated based on the average ratio of silicon metal: ferrosilicon in the other three global markets (1:0.62); The price of silica fume in the US has been assumed to be the same as in Europe.

Table 25: Currency conversion rates assumed (1 INR = 1 Indian Rupee and 1 RNB = 1 Chinese Yuan)

1 US$	0.797 €
1 INR	0.014 €
1 RNB	0.126 €

Based on these figures minimum and maximum economic coefficients were calculated according to equations 2.3 & 2.4, modified from (Chen et al., 2010), where €.m is the price per tonne (€/t) multiplied by the number of tonnes produced in the process.

$$\mathbf{C}_{\mathbf{e(max)}} = \frac{(\text{€}.\mathbf{m})_{\mathbf{by-product\ (max)}}}{(\text{€}.\mathbf{m})_{\mathbf{main\ product(min)}} + (\text{€}.\mathbf{m})_{\mathbf{by-product\ (min)}}} \qquad \textit{Equation 2.3}$$

$$\mathbf{C}_{\mathbf{e(min)}} = \frac{(\text{€}.\mathbf{m})_{\mathbf{by-product\ (min)}}}{(\text{€}.\mathbf{m})_{\mathbf{main\ product(max)}} + (\text{€}.\mathbf{m})_{\mathbf{by-product\ (max)}}} \qquad \textit{Equation 2.4}$$

Table 26: Calculated maximum and minimum economic coefficients for SF from Si and SiFe75%

Market	SF derived from Si metal		SF derived from FeSi75%	
	Ce_{min}	Ce_{max}	Ce_{min}	Ce_{max}
India	7.0%	10.8%	7.0%	10.8%
US	3.7%	5.8%	3.5%	5.1%
China	3.0%	7.3%	3.4%	7.4%
Europe	4.3%	6.8%	4.5%	6.8%

Both the mass coefficients and economic coefficients were then applied to the impacts associated with the primary processes, which were identified from literature.

The total emission factor reported by the Intergovernmental Panel on Climate Change (IPCC) for ferrosilicons is 3.91 tCO_2/t FeSi(75%) (IPCC, 1996). The IPCC have based their emission factors on FeSi75%, considered representative of ferrosilicons produced in Norway, the largest producer in Europe. Sjardin (2003) reports a lower value of 2.93 tCO_2/t FeSi(75%) . This study considered the two values as a range: 2.9-3.9 tCO_2/t FeSi (75%).

For silicon metal the IPCC reports a value of 4.3 tCO_2/t Si (IPCC, 1996). Sjardin (2003), however, considers a slightly higher value of 4.49 tCO_2/t Si from the work of Olsen et al. (1998), more representative of silicon production in Norway. Again these two values are presented here as a range 4.3-4.5 tCO_2/t Si. These carbon emission figures are based on the carbon content of the raw materials, namely the reducing agents (typically coal or coke) and the electrodes (typically produced from a paste of petroleum coke and coal-tar pitch) (Sjardin, 2003). These figures, which do not include carbon emissions associated with electricity production, are indicative of Scandinavian production, where energy production is primarily from renewable forms of electricity generation. The EC in other regional markets will be higher.

Hammond and Jones (2009) give the EE for the production of silicon as 2355 MJ/kg They acknowledge that this figure is only from a single source and the origin of this data is not given. In the absence of a more reliable figure, this value had been assumed for the EE of silicon. The EE of ferrosilicon is also not known; for this analysis it has been assumed to be 2041 MJ/kg, based on the same ratio as the EC values given for silicon and ferrosilicon production.

Table 27 shows the calculated EC and EE for silica fume based on mass and economic allocation of impacts associated with silicon metal (a) and ferrosilicon production (b). In the case of economic allocation, maximum and minimum global spot prices have been used to calculate upper and lower values. Part (c) tabulates weighted values for SF production based on the reported ratio of the two primary silicon-metal products.

Table 27: EE and EC of silica fume on the basis of mass and economic allocation

(a) Silicon production

	Units	Primary Process	Secondary Process	Impact based on mass allocation (C_m = 31%)	Impacts based on minimum economic impact ($C_{e\ (global\ min)}$ = 3.0%)	Impacts based on maximum economic impact ($C_{e\ (global\ max)}$ = 10.8%)
Embodied energy	MJ/t	2,355,000	18	730,100	72,500	254,800
Embodied CO_2	$kgCO_2$/t	4,300	14	1,300	100	500

(b) Ferrosilicon production

		Primary Process	Secondary Process	Total based on mass allocation (C_m = 18%)	Impacts based on minimum economic impact ($C_{e\ (global\ min)}$ = 3.4%)	Impacts based on maximum economic impact ($C_{e\ (global\ max)}$ = 10.8%)
Embodied energy	MJ/t	2,041,000	18	367,400	69,400	221,000
Embodied CO_2	$kgCO_2$/t	2,900	14	500	100	300

(c) Weighted silicon metal production (80% Ferrosilicon, 20% Silicon)

		Weighted total for SF, based on mass allocation	Weighted total impacts for SF based on $C_{e\ (global\ min)}$	Weighted total impacts for SF based on $C_{e\ (global\ max)}$
Embodied energy	MJ/t	439,900	70,000	227,800
Embodied CO_2	$kgCO_2$/t	700	100	300

Effect of Allocation Method on EC and EE

To understand the sensitivity of the analysis to alternative methodological assumptions the data was used to build four alternative environmental impact cases for lime-pozzolan concrete (IV) with a 28-day compressive strength of 49 MPa. The four comparative cases were:

(1) GGBS and SF considered having zero embodied impacts.
(2) GGBS and SF as 'waste' in which only impacts associated with secondary processes are considered.
(3) Environmental impacts of SF and GGBS assigned by mass allocation.
(4) Environmental impacts of SF and GGBS assigned by economic allocation.

The embodied impact of the CEM I concrete of equivalent strength was clearly unaffected by the choice of methodological assumption, as it did not contain any aluminosilicate by-products, but the same analysis was undertaken for the CEM III/A concrete (containing 50% GGBS) for comparison.

Results and discussion

Mechanical properties of lime-pozzolan concretes (0-III)

The compressive strength development of the four new lime-pozzolan concretes prepared for this study is shown in Figure 28.

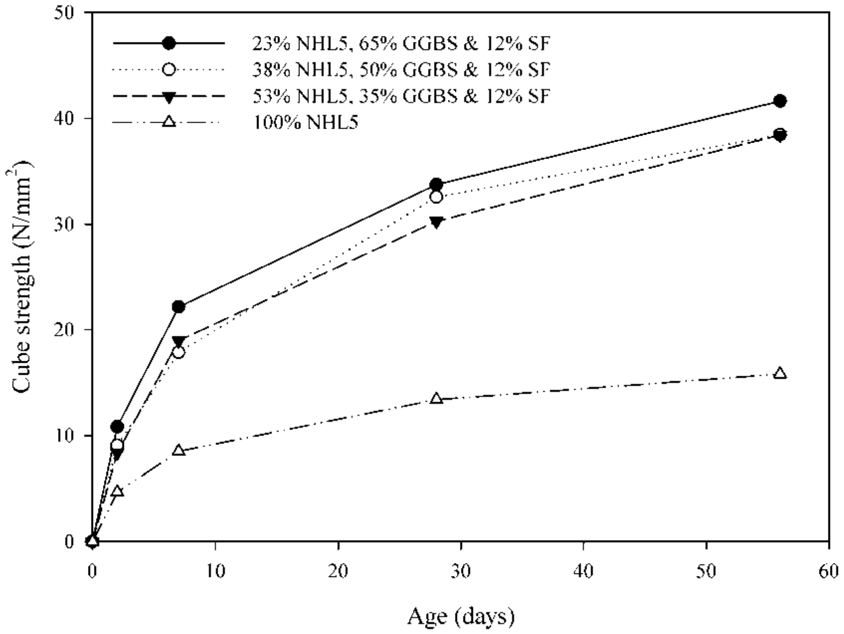


Figure 28: Lime-pozzolan concrete compressive strength development

It was observed that varying the ratio of NHL5:GGBS had minimal impact on the compressive strength development of the resulting lime-pozzolan concretes. The ternary binder comprising 23% NHL5, 65% GGBS and 12% SF resulted in the highest cube strengths at all ages, but was only 2.5-3.5 MPa higher than the lowest strength mix, which at 28-days was 53% NHL5, 35% GGBS and 12% SF. All three ternary lime-pozzolan concretes substantially outperformed the lime-concrete control, which attained a 28-day cube strength of 13.4 MPa. The rate of strength gain in the ternary lime-pozzolan concretes was observed to be greater than in the control lime-concrete at all ages. All the concretes showed a substantial strength increase between 28 and 56 days and would be expected to continue to gain strength after 56 days (Grist et al., 2013b).

Early age strength gain of lime-based concretes has previously been of particular concern (Yallop, 2013). It can be observed from the results in Figure 28 that these lime-pozzolan concretes gained around 60% of their 28-day strengths in the first 7 days. Approximately 30% of the 28-day strength was attained in the first 2 days after casting. The strength development of these lime-pozzolan concretes may be classified as ‘slow- medium’, in accordance with BS EN 206-1 (2000). As would be expected, the 28-day compressive strengths of these three lime-pozzolan concretes was substantially less than that of lime-pozzolan concrete (IV), which had a higher overall binder content.

The cylinder strength (f_c), elastic modulus (E_c), compressive strain at the maximum stress (ε_{c1}) and ultimate strain (ε_{cu1}) for each of the four lime-pozzolan concretes are shown in Table 28.

Table 28: 28-day elastic properties of lime and lime-pozzolan concretes

	f_{cyl}	E_c	ε_{c1}	ε_{cu1}
	MPa	GPa		
100% NHL5 (0)	12.0	17.4	0.0029	0.0098
53% NHL5, 35% GGBS & 12% SF (I)	27.1	32.5	0.0014	0.0014
38% NHL5, 50% GGBS & 12% SF (II)	27.7	28.4	0.0015	0.0015
23% NHL5, 65% GGBS & 12% SF (III)	29.0	17.4	0.0028	0.0028

Although the cylinder strengths of the three ternary lime-pozzolan concretes were observed to be similar, the results show that the ratio of NHL5 to GGBS has a marked impact on the elastic modulus. It can be seen that reducing the proportion of GGBS in the ternary combination, increased the elastic modulus and reduced the strain at failure by the composite concrete. The observed reduction in elastic modulus, associated with a higher content of aluminosilicate additions, agrees with the findings of Nassif et al. (2005) in CEM I-based concretes.

The elastic moduli of lime-pozzolan concretes (I-III), with 28-day cylinder strengths of around 27 MPa, are reasonably accurately predicted by equation 3.1 for CEM I-based concretes, given in Eurocode 2 (EC2), (BS EN 1992-1-1, 2004) which would predict an elastic modulus of 30 GPa. Equation 3.1 is also seen to be applicable to the control lime-concrete (0), which had both a low strength and a low elastic modulus.

$$E_{cm} = 22\,[f_{cm}/10]^{0.3} \qquad \textit{Equation 3.1}$$

In EC2, for concrete classes ≤ C50/60, the lowest value of ε_{c1} assumed for ultimate limit state design is 0.0024. Two of the lime-based concretes in Table 28 demonstrated a strain at failure less than 0.0024 and would therefore require a more conservative elastic design approach.

Given the similarity in the strength development of the three ternary lime-pozzolan concretes, the average 28-day cube strength of these three concretes (f_{c28} = 33.0 MPa), was utilized to facilitate a comparison with a single strength CEM I and CEM III/A reference concrete. A 28-day cube strength of 33.0 MPa. The control lime-concrete, having a substantially lower compressive strength (f_{c28} = 13.5 MPa), has been compared with equally low-strength CEM I and CEM III/A concretes.

Embodied CO_2 and energy comparison

Table 12 shows the calculated EC and EE of the lime-pozzolan concretes, alongside that of the CEM I and CEM III/A reference concretes of the same 28-day compressive strength.

Table 29: Embodied impact comparison

Concrete mix	28-day cube strength	w/b ratio	Embodied CO_2	Embodied energy	CO_2 Intensity, $ci_{cs\text{-}28}$	Energy Intensity, $Ei_{cs\text{-}28}$
	MPa		$kgCO_2/m^3$	MJ/m^3	$kgCO_2/(m^3 Mpa)$	$MJ/(m^3 Mpa)$
NHL5-concrete (inc. SP[1]) (0)	13.5	0.40	305	1275 (1365)	22.6	94.4 (101.1)
CEMI	13.5	1.00	170	675	12.6	50.0
CEMIII/A [50% CEMI & 50% GGBS]	13.5	0.82	115	550	8.5	40.7
53% NHL5, 35% GGBS & 12% SF (inc. SP[1]) (I)	33.0	0.40	175	890 (965)	5.3	27.0 (29.2)
38% NHL5, 50% GGBS & 12% SF (inc. SP[1]) (II)	33.0	0.40	135	795 (860)	4.1	24.1 (26.1)
23% NHL5, 65% GGBS & 12% SF (inc. SP[1]) (III)	33.0	0.40	95	695 (755)	2.9	21.1 (22.9)
CEMI	33.0	0.64	265	1045	8.0	31.7
CEMIII/A [50% CEMI & 50% GGBS]	33.0	0.58	160	790	4.8	23.9
50% NHL5, 40% GGBS & 10% SF (inc. SP[1]) (IV)	49.0	0.35	195 (195)	1190 (1310)	4.0 (4.0)	24.3 (26.7)
CEMI	49.0	0.48	345	1570	7.0	32.0
CEMIII/A [50% CEMI & 50% GGBS]	49.0	0.38	235	1355	4.8	27.7

1. *Including addition of superplasticiser at the dosage required to produce a hydraulic lime-pozzolan concrete with a slump of around 140mm.*

The results shown in Table 29 demonstrate the critical importance of comparing mixes of equal functional performance. Despite NHL5 having a lower EC than CEM I and CEM III/A binders on a mass-for-mass basis, the results show that the CO_2 intensity of the NHL5 (only)-concrete (0) is almost twice that of the equivalent strength CEM I and almost three times that of the equivalent strength CEM III/A concrete. This refutes the use of NHL5 with no pozzolanic additions as a low carbon alternative to CEM I (although other performance benefits are relevant in many applications).

On the other hand the calculated CO_2 intensity, that is the amount of CO_2 emitted in the delivery of 1 MPa of compressive strength at 28-days (Damineli et al., 2010), of each ternary lime-pozzolan concrete is shown to be lower than CEM I concretes of the same 28-day cube strength, demonstrating that NHL is effective in conjunction with appropriate pozzolanic additions. Furthermore lime-pozzolan concretes (II), (III) and (IV) are seen to have lower carbon intensities than the best practice CEM III/A concretes of equivalent strength. The CO_2 intensities of all the concretes tested, except the NHL5-only concrete, fell within the range 1.5 to 15 kg CO_2/(m^3 MPa) reported in literature (Damineli et al., 2010).

Considering the lime-pozzolan concrete with a compressive strength of 49 MPa, it can be seen that the EC of this ‘high-strength’ concrete is 43% lower than the CEM I and 17% lower than the CEM III/A concrete of equivalent strength. The necessary addition of superplasticiser (SP), at a dosage of 1.2% by mass of binder in this case, was shown to have no significant impact on the EC of the lime-pozzolan concrete (IV). The addition of SP has, however, been shown to have a substantial impact on the EE of the resultant lime-pozzolan concrete (as seen in Table 29). Including SP, the EE of lime-pozzolan concrete (IV) is around 17% lower than the equivalent CEM I concrete; excluding SP it is 24% lower. The EE of the lime-pozzolan concrete, excluding SP, is seen to be 12% lower than that of the CEM III/A concrete, and including SP, marginally lower (3% reduction).

The concrete with the lowest EC was lime-pozzolan concrete (III), which contained a high proportion of aluminosilicate minerals. This concrete had an EC of 95 kgCO_2/m^3, 64% lower than a CEM I concrete of equivalent strength. This is also 41% lower than a CEM III/A concrete of equal strength.

The EE data is presented with and without an allowance for SP in the case of each lime-pozzolan concrete. All four lime-pozzolan concretes had energy intensities less than the comparative CEM I concretes, even with an allowance for SP, but only mixes (III) and (IV) had energy intensities less than the best-practice CEM III/A concrete.

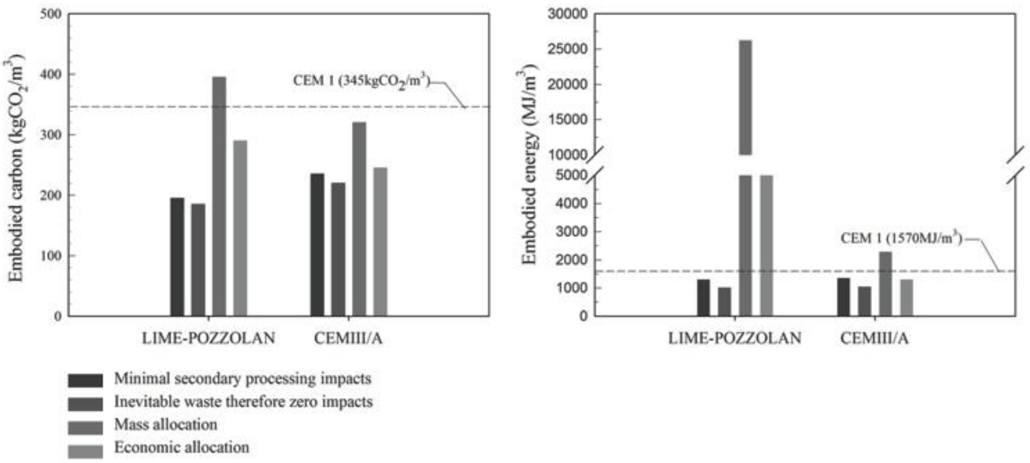
The binder intensity ($bi_{cs\text{-}28}$), or total amount of binder to deliver 1 MPa of compressive strength at 28-days (Damineli et al., 2010), of lime-pozzolan concretes (I), (II), & (III), having a typical 28-day cube strength of around 33 MPa and requiring 465 kg/m^3 of binder, is 14.1 kg/(m^3 MPa). Whereas the binder intensity of lime-pozzolan concrete (IV), having a 28-day cube strength of 49 MPa and requiring 546 kg/m^3 of binder, is 11.0 kg/(m^3 MPa). This demonstrates that the lime-pozzolan binder was more efficient at higher compressive strengths and agrees with the findings of Damineli et al. (2010) in CEM I-based concretes.

Although these binder intensity values are located within the range of results reported by of Damineli et al. (2010), it is difficult to compare these efficiencies with external data as the strength of each concrete is not only a function of the efficiency of the binder, but also of other mix design and methodological choices. For instance the resultant compressive strength is also a function of the nature and grading of the aggregates, the particle packing of the binder, the use of superplasticisers and the curing conditions. Given that the use of superplasticiser and inclusion of 6-10% SF are recommended as ways to improve the efficiency of CEM I-concrete mix designs, the scope for improving the efficiency of lime-pozzolan concretes may be limited. Other strategies for increasing the efficiency of lime-pozzolan binders will no doubt include: optimising the ratio of constituent binders both for chemical composition and/or particle packing, tailoring a blended superplasticiser, selecting suitable aggregates and identifying optimised curing conditions.

Combining these results we can postulate that a lime-pozzolan concrete containing a high proportion of GGBS, as in binder (III), and an increased overall binder content is likely to yield a concrete with a lower still CO_2 and energy intensity.

Sensitivity analysis

Figure 29 graphically compares the EC (a) and the EE (b) of lime-pozzolan, CEM III/A and CEM I concretes of the same strength (49 MPa) based on four alternative allocation methodologies.



(a) Embodied CO_2 comparison **(b) Embodied energy comparison**

Figure 29: Effect of four different allocation procedures on the EC (a) and EE (b) of three alternative concretes (f_c=49MPa)

This study demonstrates the pronounced effect of selecting different allocation methodologies in calculating the environmental impacts of cementitious binders including mineral 'by-products'.

It can be seen from these results that the choice of allocation procedure would have a fundamental effect on the selection of the 'greenest' binder. Whereas in the case of GGBS it has been shown that economic allocation procedures maintain environmental benefits in comparison to CEM I, both mass and economic allocation procedures have a very detrimental effect on the environmental credentials of silica fume.

Looking at embodied-CO_2 of the lime-pozzolan concrete (Figure 29(a)), both mass and economic allocation procedures are seen to negate any reduction in impact in comparison to CEM III/A concretes and mass allocation to negate any reduction in impact in comparison to CEM I. Looking at embodied energy (Figure 29(b)), whereas economic allocation preserves some advantage in the specification of CEM III/A as opposed to CEM I, mass allocation would suggest that CEMI is the solution with the lowest embodied energy. Given the very detrimental effect of both allocation procedures on the embodied energy credentials of silica fume, then this analysis would suggest that lime-pozzolan concretes are the most energy-intensive solution by far.

The particularly deleterious outcome of this analysis for silica fume, and thus also for lime-pozzolan concretes, highlights why it is important that issues of nomenclature do not unintentionally undermine the sensible and sustainable closed-loop utilization of materials as the allocation of impacts has no effect on global environmental impacts. Rather interoperable systems that promote the flow of materials and prevent waste must be designed and protected (Desrochers, 2004). Two extreme scenarios can be imagined that would indicate failure of the overall system: clearly it would have failed if the use of alumino-silicious 'by-products' was abandoned by the cement industry and these materials tended once again towards 'waste'; equally the production of silicon metal as a by-product of the industrial production of aluminosilicates for 'green' cement manufacture is clearly an example of high-level system failure. Although these scenarios represent extreme cases, they serve to highlight the consideration that needs to be given to the regulation of allocation procedures.

Standard methodologies are clearly needed to prevent manipulation and engender confidence in the results of Life Cycle Assessments (LCAs), however standardisation of allocation procedures is proving hugely challenging and controversial for policy makers (Heijungs and Guinée, 2007, Reap et al., 2008, Yellishetty et al., 2009, Suh et al., 2010) especially in the concrete industry (Chen et al., 2010, Van den Heede and De Belie, 2012). One recent model that might warrant further consideration in the case of lime-pozzolan technology is that proposed by Habert (2013), which considers the economic behaviour of energy-intensive industries subject to the European Union Greenhouse Gas Emission Trading Scheme (EU-ETS). The objective of this allocation methodology is to fairly distribute economic gains and losses, associated with CO_2 emissions, between the industries producing mineral additions as by-products and the concrete industry.

Conclusions

This paper reflects on the value of lime-pozzolan concrete technology in the context of the industry wide search for low carbon cements. The results of these three studies are thought to be valuable in the dialogue about the desirability and viability of this emerging lime-pozzolan binder technology. Furthermore, the results are interesting more generally in the formulation of low-carbon cementitious binders and the shaping of LCA allocation policies.

A comparison of the embodied impacts of a NHL (only)-concrete with that of a CEM I concrete of equivalent strength has revealed that the use of NHL5 alone as a ‘green’ alternative binder to CEM I is not practical. However, the use of NHL5 in conjunction with pozzolanic materials has been shown to be a viable ‘low-CO_2’ alternative to CEM I or CEM III/A in certain circumstances. For example this research has shown that a lime-pozzolan concrete with a binder comprising 23% NHL5, 65% GGBS & 12% SF, with a compressive strength of 33MPa has an EC 64% less than a CEM I concrete of equivalent strength. The EC of this concrete is also around 40% less than an equivalent strength CEM III/A concrete. The EE of this lime-pozzolan concrete is 28-33% lower than that of the CEM I concrete (depending on inclusion of SP) and 4-12% lower than that of the CEM III/A concrete.

Although this paper demonstrates that the use of aluminosilicate by-products, specifically GGBS and SF, in combination with NHL5 can realise savings in environmental impact, it has also shown that the ‘savings’ are highly dependent on the choice of allocation procedure. Whereas, in the case of GGBS it has previously been shown that economic allocation procedures maintain environmental benefits in comparison to CEM I; both mass and economic allocation procedures are shown to have a very detrimental effect on the environmental credentials of SF.

Choice of allocation methodology, for quantifying the impact of the aluminosilciate by-products, is not the only design decision shown to have a bearing on the ecological performance of lime-pozzolan concretes. This study also shows that the mix design, and the resulting compressive strength, has an effect on the appropriate use of lime-pozzolan concretes. Specifically the binder intensity of the lime-pozzolan concrete was found to vary between 11.0 kg/(m^3 MPa) for a 28-day cube strength of 49 MPa and 14.1kg/(m^3 MPa) for a 28-day cube strength of 33 MPa, demonstrating that the binder is more efficient at higher compressive strengths.

The NHL5 utilised in this research programme was reported to have a lower EC and EE than CEM I on a mass-for-mass basis. Generally, the stoichiometric chemistry and manufacturing process of NHL5 suggest both latent raw-material (RM-CO_2) and fuel-derived (FD-CO_2) CO_2 emission savings, in comparison to CEM I production. Given the considerable investment that the CEM I industry has made in improving kiln efficiencies, it is recognised that these CO_2 emission reductions are unlikely to be realised across the board without similar investment in efficient lime-kiln technologies, and that the ecological benefits associated with lime and lime-based materials are in some cases future-orientated. The availability of the raw material, the familiarity of the manufacturing process and the possibility of achieving the necessary kiln temperatures using alternative fuels, such as biomass, make lime-technology in construction interesting from both a historical and future perspective.

This study of the EC and EE of lime-pozzolan concretes suggests that these concretes could reasonably be advocated as a low- CO_2 alternative to Portland-cement concretes. Given that the ecological performance of this concrete has been shown to influenced by the source of NHL5, the choice of allocation methodology, the ratio of constituent materials, the total binder content and the use of superplasticisers, it is recommended that caution is exercised by those promoting or specifying this novel technology purely on the basis of its ‘green’ credentials. That said there is scope for the careful design, specification and production of lime-pozzolan concretes that could realise substantial CO_2 emission savings.

It is thought that the future development of lime-pozzolan concretes lies not in its ecological performance alone, but rather in the combination of ecological and technical performance benefits. Before construction professionals and building owners were even conscious of global warming, they were selecting lime-based building materials over their cement-based alternatives because of their preferential performance in use. Specifically research is needed to understand the breathability, permeability and durability of lime-pozzolan concretes and how these properties are affected by the nature and proportion of aluminosilicate additions. Further testing might also consider the technical and ecological performance of lime-pozzolan concretes based on alternative synthetic or naturally occurring pozzolanic materials.

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9 Research findings

Given that the findings of this research are reported across five discreet journal papers, they have been collated here in a single list. This list must be read in conjunction with the individual papers, which describes the testing and presents the results that substantiate and contextualise these research findings. This section concludes with a description of the key contribution to knowledge offered by this materials research.

9.1 Phase 1: Development of high strength lime mortars

Paper 1: Grist, E.R., Paine, K.A., Heath, A. and Norman, J., (2013). Compressive strength development of binary and ternary lime-pozzolan mortars. Materials and Design. 52:pp514-523

- Hydraulic lime-pozzolan mortars prepared in the lab using modern pozzolanic Type II additions can attain 28-day compressive cube strengths of over 25.0 N/mm^2.
- A ternary combination of SF and GGBS can have a Pozzolanic efficacy of 94% and result in a mortar eight times as strong as a mortar prepared with NHL5 alone.
- Aluminosilicate additions can be combined with a complimentary effect. For example the use of MK is beneficial in combination with both GGBS and FA.
- A ternary combination of NHL5, SF and GGBS produced resulted in mortars with the highest 28-day compressive strengths.
- Plotting Pozzolanic Efficacy, PE (%) against time is a powerful graphical method for describing the relative contribution of the pozzolanic additions to the process of strength development in lime-pozzolan cementitious systems.
- It is notable that this work also highlighted a limitation in the mortar testing standards with regards to curing in a range of conditions and appropriate preparation of the mortars for mechanical testing. Specifically it is has been noted that neither BS EN 1015-11:1999 [1] nor BS EN 196-1 [2] explicitly deal with the moisture condition at which compressive strength tests should be performed.

9.2 Phase 2: Development of structural lime-concrete

Paper 2: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). Structural and durability properties of hydraulic lime-pozzolan concretes. Accepted for publication in Cement and Concrete Composites. 2014

Paper 4: Structural limecrete: an investigation into the potential of hydraulic lime-concrete using pozzolanic and latent hydraulic additions. SCI Young Researchers Conference. Thursday 17 May 2012: London.

Paper 5: Grist, E., Paine, K., Norman, J. and Heath, A., 2012. The feasibility and potential of modern hydraulic lime concretes. In: Concrete Structures for Sustainable Community, Fib Symposium, 2012-06-10 - 2012-06-14, Stockholm.

- 'Structural strength' (assumed to be > 30MPa) lime-pozzolan concretes are technically feasible. 28-day cube strengths of 35MPa were attained by water-cured lime-pozzolan concretes
- The production of lime-pozzolan concretes at low w/b ratios results in the strongest and most durable concretes.
- Lime-pozzolan concretes cannot be adequately compacted at low w/b ratios (<0.5) without the addition of a suitable water-reducing admixture.
- The greatest initial and long term strength gain, the highest strain at the maximum compressive strength (ε_{c1}), the greatest carbonation resistance and the least drying shrinkage, was exhibited by a lime-pozzolan concrete comprising 50% NHL5, 25% SF and 25% GGBS.
- SF or an alternative source of soluble silica is a key constituent of high strength lime-pozzolan concretes.
- Although this study has demonstrated unprecedented compressive strengths (greater than the 17 MPa hydraulic lime – metakaolin concretes produced by Cachim et al. (2010) [4]), initial lime-pozzolan concretes exhibit only moderate strengths and tolerable durability in comparison with the reference PC-concretes.

9.3 Phase 3: Suitability for manufacturing

Paper 3: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). Lime-pozzolan concretes: addressing project-specific questions. Accepted for publication in Construction Building Materials. 2014.

- A number of commercially available PCE superplasticisers can be employed to produce workable and high strength lime-pozzolan concretes.
- The required dosage of PCE superplasticiser tended to be higher than that recommended for PC systems.
- The addition of 10% SF tended to reduce the demand for SP unlike in PC systems.

- Addition of 1.2% SP was seen to increase the 28-day strength of an NHL5 mortar from 3.2 to 12.6 MPa.
- The highest strength lime-pozzolan mortars were attained using a fourth-generation PCE superplasticiser, containing a synthetic co-polymer.
- The influence of alternative SPs on compressive strength development was seen to have the greatest impact in the first 7-days.
- Inclusion of 10% SF in the NHL3.5 mortar resulted in a 28-day compressive strength of 31.6 MPa, three times the strength attained by the NHL 3.5 alone (10.3MPa).
- The greatest increase in compressive strength was attained in the mortar prepared with 50% NHL 3.5, 40% GGBS and 10% SF. At 28-days the compressive strength this mortar was 37.3 MPa, 3.6 times higher than the equivalent mortar prepared with NHL 3.5 alone.
- It is possible for a ternary lime-pozzolan concrete (56% NHL5, 34% GGBS & 10% SF) to attain an air-cured compressive strength of 49 MPa at 28-days increasing to 65 MPa at 90-days.
- Three of the four concretes tested in this programme attained a 28-day cube strength greater than 40 MPa.
- Cold-weather curing reduces the 28-day strength of lime-pozzolan concretes by up to 44%.
- Lime-pozzolan concretes can be cast into structural elements with a finished surface and appearance similar to CEMI-concrete.
- In the lime-pozzolan beams the central deflection at the point of failure was 40% higher than the equivalent deflection of the CEMI concrete beams. This suggests that some modification may be appropriate in the serviceability limit state (SLS) design of lime-pozzolan concrete elements.
- The fundamental principles for the design of concrete structures, embodied in EC2 [3], be employed for the conservative design of structural lime-pozzolan elements.
- In comparison to the strength enhancement observed with the addition of 10% SF to an NHL3.5 mortar, there is little to differentiate the strength development of the three hydraulic lime mortars NHL2, NHL3.5 and NHL5.

This raised a question about the relative performance of the three hydraulic limes in combination with pozzolanic additions. The higher free lime content of NHL3.5, or NHL2, might further enable the pozzolanic reaction and enhance the lime-pozzolan binder. Given

NHL3.5 has a lower embodied CO_2 and energy than NHL5 [5], the results suggest that this moderately-hydraulic lime warrants further investigation in the development of future lime-pozzolan binders. Such future testing might investigate how the use of NHL3.5 affects not only mechanical strength, but also the porosity and permeability of the resulting lime-pozzolan concretes.

It is suggested that a blended PCE superplasticiser might in future be specifically designed for binary or ternary lime-pozzolan binders, which would minimise the overall required dosage and thus also the embodied impact of the resulting lime-pozzolan concrete. Specific modelling of the zeta potential of the constituent minerals in aqueous solution is thought to be required to understand the absorption mechanism of PCE superplasticisers in binary and ternary lime-pozzolan binders.

9.4 Phase 4: Environmental benefits

Paper 6: Grist, E.R., Paine, K.A., Heath, A. and Pinder, H., 2013. An Investigation into the Viability and Benefits of Modern Hydraulic Lime Pozzolan Concretes. In: Dhir, R. K., Singh, S. P. and Goel, S., eds. Innovations in Concrete Construction. New Delhi: Excel India Publishers, pp. 967-981

Paper 7: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). The environmental credentials of lime-pozzolan concretes. Accpeted for publication in the Journal of Cleaner Production. 2014.

- The use of NHL5 alone as a ‘green’ alternative binder to CEMI is not practical.
- The use of NHL5 in conjunction with pozzolanic materials has been shown to be a viable ‘low-CO2’ alternative to CEMI or CEMIII/A in certain circumstances.
- A lime-pozzolan concrete with a binder comprising 50% NHL5, 40% GGBS & 10% SF and a strength of 49 MPa has an embodied CO2 43% less than a CEMI concrete of equivalent strength. The embodied CO2 of this concrete is also 17% less than an equivalent strength CEMIII/A concrete. The embodied energy of this lime-pozzolan concrete is 17-24% lower than that of the CEMI concrete (depending on inclusion of SP) and is 3-12% that of the CEMIII/A concrete.
- Potential savings in the embodied CO2 and energy of lime-pozzolan concretes are highly dependent on the boundaries of the analysis
- Particularly in the case of SF, classification of aluminosilicates as ‘by-products’ could have serious implications on their inclusion in ‘green’ concretes.

- Lime-pozzolan binder are more efficient at higher compressive strengths. Specifically the binder intensity of the lime-pozzolan concrete was found to 11.0 kg/(m3 MPa) for 28-day cube strength of 49 MPa and 14.1 kg/(m3 MPa) for 28-day cube strength of 33 MPa respectively.
- There is scope for the careful design, specification and production of lime-pozzolan concretes that could realise CO2 emission savings.

9.5 Phase 5: Bespoke adaptation

Paper 8: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). Innovative solutions please, as long as they have been demonstrated elsewhere. Case Studies in Construction Materials. January 2014

This is a list of key findings pertaining to the technical performance of the lime-pozzolan developed for this specific project:

- Use of site-won frost shattered oolitic limestone (FSOL) as all-in aggregate produced a lime-pozzolan concrete demanding an atypically high dosage of superplasticisers (3.2% by mass of binder).
- Limiting the FSOL to that of 'coarse aggregate' (6.3-28mm) and blending with 34% Marlborough grit reduced the demand for superplasticiser.
- A lime-pozzolan concrete, with FSOL aggregate, attained a maximum 28-day cube strength of 26 MPa, at a w/b ratio of 0.35. This concrete gained around 75% of its 28-day strength in the first 7 days. Of this, 30-40% of the 28-day strength was attained in the first 3 days after casting.
- Lime-pozzolan concretes can be diamond polished after 2 weeks, as per Portland cement concrete and sealed with proprietary sealants. The embodied CO2 of a 100 mm thick polished lime-pozzolan concrete floor is 45% less than a typical 100mm thick polished CEMI-concrete floor and 25% less than a conventional vinyl floor makeup. The embodied energy of a 100mm thick polished lime-pozzolan concrete floor is 21% less than a typical 100mm thick polished CEMI-concrete floor and 37% less than a conventional vinyl floor makeup. The reinforcing mesh in a 100 mm thick polished lime-pozzolan concrete floor slab can account for 43% of the embodied energy per m2. It was shown that the CO2 emissions resulting from the necessary transportation of hydraulic lime from France to the UK were minimal (around 40 kgCO2/t) in comparison to those associated with the manufacture of the binder (635 kgCO2/t) and

that therefore additional transport impacts cannot therefore be used as a legitimate argument for choosing to use a locally available CEMI as an alternative to hydraulic lime.

10 Contribution to knowledge

This project was successful in demonstrating the feasibility of producing modern, hydraulic lime-pozzolan concretes. Demonstrating that lime-based concretes can attain 28-day compressive strengths of up to 50MPa is a step-change for lime-based construction materials. The results confirm the potential use of lime-concrete as an alternative to Portland-cement concrete for structural components, an idea that was described by Holmes and Wingate in 1997, who appreciated then that this was not an area of science that had been developed.

This research also provided evidence that hydraulic lime-pozzolan concretes containing a high proportion of aluminosilicate minerals could have an embodied CO2 of 95 $kgCO_2/m^3$, 64% lower than a CEMI, and 41% lower than a CEMIII/A, concrete of equivalent strength (see Paper 7). As well as showing the potential for 'low-carbon' lime-pozzolan concretes, the lime-pozzolan binder system might prove valuable in reducing the environmental impact of existing lime-based construction materials.

Although, these overall findings go a long way in addressing the questions of technical feasibility and environmental sustainability that initiated this research project, they do not capture the contribution to knowledge that this research offers to the scientific community at large. For the mechanical and environmental performance of these novel lime-based concretes was dependent upon the attainment of compressive strengths that are believed to be unprecedented in the wider field of lime-based construction materials.

The graph in Figure 30 has been extracted from paper 3 and reproduced below to assist in the discussion of what is purported to be the primary contribution to knowledge in this case. The graph shows the compressive strength development of a range of NHL mortars. The exact composition of the mortars is descried in detail in paper 3, but rather one is asked to consider the relative impact of lime type (NHL2, NHL3.5, NHL5), superplasticiser addition and pozzolanic mineral addition on the strength development of lime-based mortars. It was a combination of these beneficial effects that facilitated the production of a structural strength concrete based on hydraulic lime.

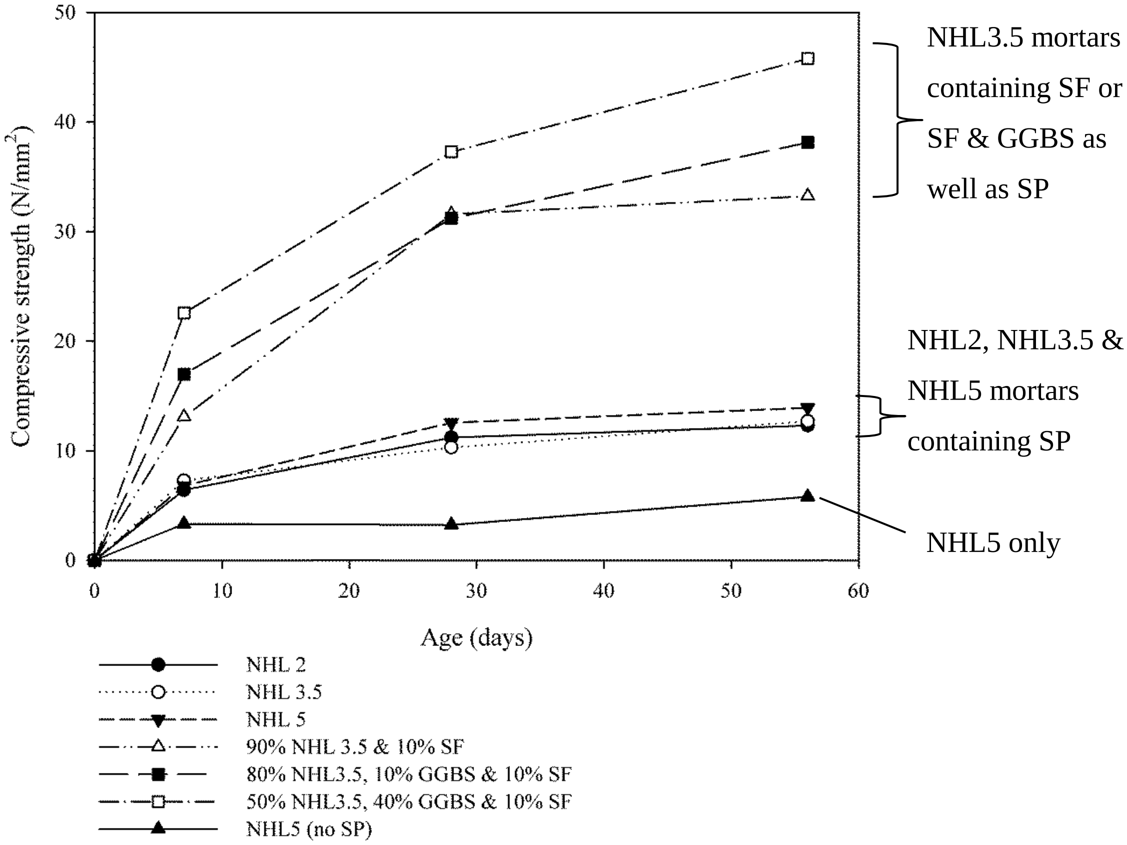

Figure 30: Compressive strength development of hydraulic lime mortars with and without SPs and aluminosilicate mineral additions

Considering the strength development of the NHL5 reference mortar (without SP), in comparison the three lime-only mortars incorporating SP, the addition of SP has been demonstrated to result in a marked improvement in the compressive strength gain of lime-mortars.

The second point of interest, indicated on the graph, is that the differential strength gain between the NHL2, NHL3.5 and NHL5 lime mortars has been shown to be minimal in comparison to the other observed phenomena. This raises questions about the relative performance of the three hydraulic limes in combination with pozzolanic additions.

Perhaps most significantly, this graph also demonstrates the substantial enhancement in strength gain associated with inclusion of the aluminosilicate mineral additions. At 28-days the mortar prepared with 50% NHL 3.5, 40% GGBS and 10% SF had attained a 28-day strength of 37.3 MPa, 3.6 times higher than the equivalent mortar prepared with NHL 3.5 alone (both containing SP). The considerable contribution of ternary combinations of modern aluminosilicate mineral additions to the mechanical strength of hydraulic lime-based binders is asserted to be the most compelling contribution to knowledge in the case of this research. For it was the pozzolanic efficacy of a ternary combination of NHL5, GGBS and SF that led to the attainment of unprecedented mechanical strengths in hydraulic-lime based concretes.

The results of this research clearly illustrate the efficacy of water reducing admixtures and reactive pozzolanic additions (and combinations thereof) in substantially increasing the mechanical strength of hydraulic lime-based binders. The mechanical performance of hydraulic lime-pozzolan binders observed in this study has not previously been seen and thus is not being exploited in current practice. Mechanical strengths comparable with those obtained in Portland-cement based concretes, considerably increases the range of potential applications of hydraulic lime in construction.

11 Limitations of this research

The primary limitation of this research is that no specific testing has been undertaken to understand the reaction chemistry and thus to explain the observed mechanical performance of lime-pozzolan binders at a macro-scale. This explanatory research will be hugely valuable in the advancement of this science and in the development of future lime-pozzolan binders. An understanding of the reaction kinetics, will assist in the selection of suitable constituents, the optimisation of the binder, the identification of possible degradation mechanisms as well as inform best practise in the use of lime-pozzolan binders in construction.

Without any chemical analysis this research has been able to offer only tentative explanations for the observed phenomena. Such explanations, where offered, have been wholly dependent on explanations derived by others working in the field of Portland-cement technology.

Although the lack of substantiated theoretical explanations does not invalidate the phenomena observed, it is recognised to make the results difficult to interpret and generalise. Without a theoretical grounding, specifically in this instance, without being able to describe the reaction kinetics or the nature of the hydration products, one is limited to the iterative trial and improvement approach facilitated by empirical test results. This approach may be effective in answering questions about the performance of novel materials but is not efficient due to the emphasis it puts on the results of empirical testing and low generalizability of the findings.

The mechanical performance of this engineering material at the macro-scale is recognised to derive from physiochemical phenomena at the micro-scale. In the case of lime-pozzolan binders the reaction kinetics are thought to be highly complex, with four chemical reactions contributing to the strength gain of these concretes:

- Hydration of the hydraulic minerals, primarily belite in the NHL5 but also hydraulic minerals present in the GGBS.
- Activation of the pozzlanic minerals in the SF and GGBS, by the CaOH (free lime) in the NHL5.
- Activation of the pozzlanic minerals in the SF and GGBS, by the CaOH produced by the hydraulic reactions.
- Carbonation of hydrates in contact with atmospheric carbon-dioxide.

It is recognised that the relative rate and extent of these four reactions, which occur more or less concurrently, will have a significant impact on the phase assemblage, pore structure and strength development of the resulting lime-pozzolan concretes and therefore is of great interest in the development of this novel concrete technology.

Looking at possible future directions for this immature concrete technology, and the number of questions these applications raise about the behaviour of these materials, the value of generalizable theoretical explanations becomes very apparent. Physiochemical analysis is purported to be a crucial next step in the development of this technology.

It is also recognised that further work is needed to appraise the value of these findings in the context of the search for low-CO_2 cementitious binders. Although the results of this research suggest that lime-pozzolan binders can have a lower-embodied CO_2 than incumbent Portland-cement based binders, it is recognised that the environmental credentials of lime-pozzolan binders are not understood in comparison to those of alternative future binder technologies that are being developed. This analysis would need to be informed by a range of geographical, industrial and macro-economic factors.

12 Further work

In line with the limitations of this study, future work is thought to rely heavily on physiochemical testing, with a variety of techniques being identified as appropriate for investigating the reaction kinetics and hydration products: isothermal conduction calorimetry, x-ray diffraction, thermal gravimetry and Fourier transform infrared spectrometry. Other techniques that might be valuable in studying the pore structure and phase assemblages include: scanning electron microscopy, mercury intrusion porosimetry and x-ray computed tomography.

With this in mind, future work has been discussed in the context of future directions for this innovative binder technology.

13 Future directions for the technology

In line with the aims of this tranche of the research programme, laboratory testing and initial field trials have demonstrated the technical feasibility of producing low-CO_2, structural grade lime-pozzolan concretes. The objective of the research presented in this section was not to discover a unique formula for a new marketable product, which might at some level compete with Portland cement (CEMI); but rather to push on the boundaries of lime technology and where possible to create design space for future lime-based construction materials. That said the exposition of unprecedented structural properties unlocks potential for this lime-pozzolan technology to be evaluated and developed as one of a number of 'second-generation' cements.

This hydraulic-lime pozzolan binder is believed to be an incremental innovation in the evolution of cementitious materials. Alternative technologies being developed concurrently with this one are arguably more radical innovations in the field of cement technology and ultimately have the potential to deliver greater environmental benefits than a cement dependant on calcination. It is however conceivable that the long and rich history of lime in construction, will bestow some short-term market advantage on lime-pozzolan concretes in comparison with other less familiar and more disruptive technologies. In the case of this binder, technological similarities with CEMI, such as being manufactured by the calcination of limestone and the potential to be blended and bagged as a dehydrated mixture to which water can just be added, are seen as advantage in the short-term and disadvantages in the long-term.

It is difficult to draw comparisons between alternative second-generation concrete technologies due to limited information in the public domain. One thing however is sure; given that CEMI is totally entrenched in modern construction practice and given economies of scale result in the relatively inexpensive production of CEMI, all novel cement-technologies face a very difficult route to market.

Although the lime industry is dwarfed by the cement industry, the fact that lime-production is established worldwide does make lime-pozzolan technology immanently reproducible at a range of scales. Lime-pozzolan concrete, being akin to a recipe, is not a disruptive technology, which might otherwise demand millions of pounds worth of capital investment in new production facilities. Rather implementation of this novel technology could begin with one, or more, early adopters; individuals who are willing to champion this innovative technology, accept the inherent risks and overcome emergent obstacles at a project scale. Given that the premium cost of specifying lime-pozzolan concretes is undoubtedly going to be one such obstacle, an analysis of the material cost of two alternative lime-pozzolan concretes has been undertaken, to reduce the cost uncertainty.

The price of two alternative lime-based concretes has been calculated and compared with two typical cement-based concretes based on the price information shown in Table 30.

The two lime-pozzolan concretes were ternary combinations of hydraulic lime (NHL5), ground granulated blastfurnace slag (GGBS) and silica fume (SF):

- 50% NHL5, 40% GGBS & 10% SF
- 30% NHL5, 60% GGBS & 10% SF

The first concrete was that developed for the eco-house and had a binder content of 545 kg/m^3 and an average 28-day cube strength of 49 MPa. The second was a concrete attained a very similar 28-day cube strength to the first when both were prepared with a total binder content of 465 kg/m^3. For the purpose of this cost analysis it was assumed that this concrete would also have attained a 28-day cube strength of 49 MPa had it also have been prepared at a binder content of 545 kg/m^3.

Table 30: Spot price of constituent materials (May 2013)

Constituent	Price/tonne (May 2013 exc. VAT)
NHL5	£380
GGBS	£160
SF	£192
Marlborough Grit	£42
Limestone aggregate	£25
SP	£1000
CEMI	£150-220

In order to be able to establish the cost premium, the cost range of two standard CEMI-based concretes, CEMI and CEMIII/A (50% CEMI & 50% GGBS), was estimated as a baseline for comparison.

The range of factors given in Table 31, describes the cost premium of the two alternative lime-pozzolan binders, over the range of prices assumed for CEMI on a mass basis.

Table 31: Estimated cost premium of two lime-pozzolan binders

	CEM I
50% NHL5, 40% GGBS & 10% SF	1.2 – 1.8
30% NHL5, 60% GGBS & 10% SF	1.0 – 1.5

On a mass-for-mass basis the cost premium is seen to range from 1.0-1.8, a factor of 1.0 implying a cost neutral choice. However the research programme has shown that in the case of lime-pozzolan concretes that a higher overall binder content (by mass) is required to attain the equivalent compressive strength. As a result the cost implications of the choice to specify a lime-pozzolan binder can only be appreciated by comparing the constituent materials in specific concretes.

Table 32: Estimated cost premium of two lime-pozzolan concretes

	CEM I	CEMIII/A
50% NHL5, 40% GGBS & 10% SF	2.1 - 3.0	2.0 - 2.5
30% NHL5, 60% GGBS & 10% SF	1.8 - 2.6	1.7 - 2.1

It can be seen from the results of this simple analysis that lime-pozzolan concretes are two to three times the cost of CEMI based concretes (of equivalent strength), based on current prices of the constituent elements. Clearly in a dynamic market in which prices fluctuate and vary dependent on purchasing scale, this cost analysis can only give a snapshot. Given that lime-manufacture demands less energy than the manufacture of Portland-cement the premium cost of lime, is purported to be principally, if not purely, a function of scale (Building Lime Forum, 2013), on which basis it is anticipated that the cost might be reduced with increased demand.

It is recognised that this analysis also only considers the cost of procuring the constituent materials and that the cost premium will in all likelihood be magnified when professional fees, including those of a building contractor, are factored in. This analysis serves to highlight one of the obstacles that all novel cementitious binders invariably face. With the global cement industry exploiting considerable economies of scale in the supply of low cost CEMI into the market, it is thought that only superior performance, in conjunction with reduced environmental impact, will see new low-CO_2 cements becoming a viable alternative.

The costing exercise is also valuable in emphasising two aspects of this innovative concrete technologies' future development that are asserted to be of strategic importance.

1. Firstly, given that hydraulic lime is currently around twice the price of Portland cement, there is a strong case for investigating the properties of lime-pozzolan concretes with a higher proportion of, and/or lower cost, aluminosilicate mineral additions, which in some cases may be capable of offsetting the cost of the hydraulic lime.

   The results of laboratory testing, reported in Paper 7 (Grist et al., 2014), has demonstrated that a lime-pozzolan binder comprising 23% NHL5, 65% GGBS and 12% SF has a 28-day strength 2.5-3.5 MPa higher than a binder comprising 53% NHL5, 35% GGBS and 12% SF. This suggests that the optimum dosage of aluminosilicate mineral additions, with respect to compressive strength, may exceed 77%. A substantial proportion of aluminosilicate mineral additions in the binder composition will be beneficial from both an economic and environmental perspective.

   Although this work has suggested that a small percentage of SF, or an alternative source of reactive silica, is critical to the early age strength gain of lime-pozzolan concretes, there is scope for investigating the performance of ternary lime-pozzolan concretes, where the third constituent, in this case GGBS, is substituted for a lower cost alternative pozzolanic material.

2. Secondly, it is imperative to identify applications where lime-pozzolan concretes will add value and where this added value might be capable of bearing some premium cost. Whereas the research programme to date has tried to reduce the difference between lime-pozzolan and CEMI concretes, subsequent research will need to identify and amplify differential properties in order to ascertain lime-pozzolans concretes unique selling point(s) (USPs), which could open up the market(s) for this alternative concrete. Whereas similarities in the mechanical behaviour of lime-pozzolan and Portland-cement concretes are thought be valuable in engendering confidence in the new technology, it is thought that differences will, at least in the short-term, provide opportunities for specifying lime-pozzolan concretes.

These two key ideas are recommended to underpin any subsequent research and development of this technology. In regard to the second point, further work has been identified in context of a strategic market analysis. The future development of lime-pozzolan concretes is discussed in the context of four primary market sectors. The value proposition of lime-pozzolan concretes is briefly discussed in each sector, with the view to identifying specific opportunities to commercialise this technology in the future.

1) Low impact buildings
2) Conservation of historic structures
3) Appropriate technology
4) Composite structural systems

13.1 Low impact buildings

Initiated by a real-world ‘green’ building project, research into this novel concrete was conducted on the basis that lime-pozzolan concrete would prove to be both a feasible and low-CO_2 alternative to Portland-cement concrete. At the outset, scepticism about the structural potential of hydraulic lime, led to reservations about the likelihood of this proving to be an ecological alternative (Ramboll Whitbybird, 2008). Retrospectively, it can be seen that it took three years of testing and development in the laboratory to arrive at a lime-pozzolan concrete offering the functional performance, in this case compressive strength, necessary to render this solution a ‘low-CO_2’ alternative to Portland-cement concrete (see Paper 7) (Grist et al., 2014).

Although CO_2 and energy savings have been identified in comparison with CEMI concrete the magnitude of the savings in comparison to specification of a CEM,III/A concrete, for example, still raise questions about the ecological progress offered by this novel technology to date. That said, the unprecedented mechanical properties of the most developed lime-pozzolan concrete thus far, might counter scepticism about the ‘green’ credentials of this immature technology. Furthermore, the results demonstrate scope for improving the eco-efficiency of future lime-pozzolan concretes (see paper 7) (Grist et al., 2014). Specifically, there is scope to optimise the relative proportions of the ternary lime-pozzolan binder to maximise desirable properties and minimise embodied impact. There is also scope for exploring the performance of ternary lime-pozzolan concretes based on alternative hydraulic-limes (NHL3.5 or NHL2) and naturally occurring and/or more widely available pozzolanic minerals.

Given that further reductions in the embodied impacts of lime-pozzolan can be anticipated (E.R. et al., 2014), further development of this concrete technology might well be propelled by the growing market for ecological building materials. As increasingly stringent building codes act to improve the operational performance of buildings, the focus of 'green' design is anticipated to shift towards embodied CO_2 and energy, which will account for an increasing proportion of the whole-life impacts of buildings (Rawlinson and Weight, 2007). The growth of 'Ecobuild', the construction industry's major showcase of sustainable products and materials', is evidence of the emerging market for ecological building materials. Since its launch in 2005, Ecobuild is reported to have almost doubled in size every year to become the biggest event in the world for sustainable design, construction and the built environment. In 2012 this event in London, attracted over 57,000 industry professionals over the course of three days (Ecobuild, 2013).

A case study investigating the embodied-CO_2 of a ten storey steel-framed commercial office building (One Kingdom Street, London) has suggested that the concrete works (substructure and core) was responsible for 18% of the overall embodied-CO_2 (dcarbon8, 2007). This implies that there is scope to substantially reduce the CO_2-footprint of new buildings by changing the specification of sub-structural concrete elements. If lime-pozzolan concretes are going to find an application in the foundations of ecological buildings, it would be beneficial to undertake some additional tests to pre-qualify the durability of the material. Durability is clearly of critical importance in the design of sub-structural elements, where structural integrity is fundamental to the long-term performance of entire structures.

Although ancient structures such as the Pantheon, via Appia, the Pont du Gard aqueduct and the Baths de Caracalla are thought to provide evidence of the durability of lime-pozzolan concrete structures, this innovative material is not a return to a former technology and utilizes modern artificial pozzolanic minerals and the latest generation of cementitious admixtures. Although testing is incapable of proving the long-term performance of materials, particularly those that might be anticipated to endure for centuries, if not millennia, it is possible to compare the relative performance of alternative concretes in the laboratory. Price (2009) purports 'It is not sustainable and not practical to use a material that has not been tried and is not durable'. Rigorous testing is still required to compare the performance of lime and cement based concretes subject to aggressive exposure conditions and other accelerated durability tests.

Durability testing of lime-pozzolan concretes to date is limited to a study of carbonation resistance. This accelerated testing suggested that 40 mm of lime-pozzolan concrete cover might adequately protect carbon steel reinforcement for 130 years (Grist et al., 2012: In Press). Although this performance might be satisfactory in some applications, the fact that the carbonation resistance was observed to be lower than that reported for CEMI-based concrete is concerning, given that carbon-induced corrosion has proved to be a substantial limitation in the longevity of CEMI concrete structures (The Concrete Society, 2000).

Carbonation resistance was tested relatively early on this study and the effect of subsequent developments in the mix design are not known. It is anticipated that the carbonation resistance will have increased, in line with the compressive strength of the concrete, although the effect of reducing the proportion of silica fume from 25% to 10% is uncertain. Further carbonation testing would be appropriate in qualifying the durability of reinforced lime-pozzolan concrete structures. Furthermore, Rapid Chloride Permeability Testing could be used to model the chloride ion diffusion coefficient of lime-pozzolan concretes. Lime-pozzolan concretes have a long history of use in aggressive marine applications; Pozzuoli Bay (Baianus Sinus), constructed in the first century BC, being just one example (Jackson et al., 2013), suggesting that modern lime-pozzolan concretes might be proved to be valuable in marine environments. Jackson et al. (2013) are studying the mineralogical structure of ancient marine concretes in order to ‘unlock the secrets’ of Roman seawater concretes.

Other physical-chemical effects that warrant further performance testing and pre-qualification in the case of lime-pozzolan concretes are resistance to sulphate attack and alkali-silica reaction.

Sub-structure concrete can be at risk of sulphate attack if there is a high concentration of water-soluble sulphates (SO_4) in the soil or groundwater. The risk of sulphate attack in hydraulic lime-pozzolan concrete is thought to be low because of the low content of C_3A. C_3A content has been described as ‘the greatest single factor influencing the resistance of Portland cement concrete to sulfate attack’ (Neville, 2004). However it is acknowledged that there are several mechanisms of sulfate attack, including a direct attack on $Ca(OH)_2$ (Neville, 2004), which need further investigation, before the sulfate resistance of lime-pozzolan concretes can be substantiated. Demonstrating that lime-pozzolan concretes are resistant to sulphate attack may provide added value to client for whom aggressive ground conditions present a problem.

Use of crushed glass as aggregate in concrete is recognised to be a beneficial way of recycling some of the millions of tonnes of post-consumer glass that enters the waste stream every year, whilst also reducing the demand for virgin aggregates. The practise of utilising waste glass in architectural concrete dates back to the 1950's but since the mid-1970's it has been recognised that this practice can result in deleterious cracking caused an expansive reaction between the alkalis in the cement and silica in the glass, a phenomena commonly known as ASR (alkali-silica reaction) (Rajabipour et al., 2010).

The risk of ASR in lime-pozzolan concrete is thought to be low because natural hydraulic lime has a low Na+ and K+ content and any Na+ and K+ present would be expected to react with the highly reactive pozzolanic materials, leaving no free Na+ and K+ in the system. Substantiation of the resistance of lime-pozzolan concrete to ASR would open up the possibility for lime-pozzolan concretes with a high recycled glass content.

It is worth noting that these durability related performance criteria are only necessary in aggressive exposure conditions and that the test results would not affect the specification of sub-structural lime-pozzolan concrete in the majority of applications.

The cost of lime-pozzolan concretes is likely to prove a major obstacle in inherently functional applications, such as foundations, where large volumes of material is cast below ground and then promptly buried. With the lime-concrete permanently obscured from view, there is little or no scope for added aesthetic or prestigious value in the long term. Given that foundations are always on the critical path, the rate of compressive strength development, exhibited by lime-pozzolan concretes tested in this programme, might prove advantageous in comparison with other commercially available lime-concretes, but disadvantageous in comparison to CEMI. Any increase in curing requirements, in comparison to CEMI, will invariably push up the cost of using lime-based concretes, due to the implications on the project programme.

It is thought that the future development of lime-pozzolan concretes lies not in its ecological performance alone, but rather in the combination of ecological and technical performance benefits. Scope for improving the ecological credentials of lime-pozzolan concretes has been identified.

13.2 Conservation of historic structures

Lime-based building materials are routinely specified for the repair and maintenance of the fabric of historic buildings. Lime-based materials exhibit a number of favourable characteristics that differentiate them from cement-based alternatives and improve their performance in use, specifically breathability, permeability and durability. On this basis research is needed to understand the porosity and capillarity of lime-pozzolan concretes and importantly how these characteristics are affected by the nature and proportion of aluminosilicate additions in the binder.

Lime-based materials typically have a high water vapour permeability, which has proved advantageous in the repair of historic structures. Cement-based materials, by comparison, have a low water vapour permeability and have been observed to lead to water induced-degradation caused by trapped moisture. Given that permeability and compressive strength are conversely affected by the porosity of the material, it is recognised that the enhancement of mechanical strength, that has steered the research to date, is likely to have been accompanied by a reduction of water vapour permeability. Before lime-pozzolan concretes find a market in the conservation of historic structures, further research is thought to be required to quantify the breathability of ternary lime-pozzolan concretes.

Lime-mortars are also advocated for autogeneous-healing; the ability for free lime to carbonate in mirocracks leading to self-healing mechanism. Whether or not lime-pozzolan concretes are also capable of being self-healing will depend on the long-term availability of free lime in the binder. This in turn will be governed by the extent and duration of the pozzolanic reaction and will be affected by the ratio of lime to pozzolan in the binder. An excess of lime could perhaps be ensured to facilitate autogeneous healing in lime-pozzolan concretes.

To a large extent properties of lime-based materials that have proved beneficial in the conservation of historic buildings are at odds with compressive strength, such that the research to date has intentionally steered away from these characteristics. Given that high compressive strengths are unlikely to be required in conservation applications, there is scope for future research in this area to work back from the high-strength concretes that this programme has converged on. Although unprecedented compressive strengths may be of little interest in this sector, the rapid speed of set and enhanced workability of lime-pozzolan concretes could be beneficial, provided other performance characteristics can be shown to be maintained.

13.3 Appropriate technology

The combination of aluminosilicate additions that have been investigated in this research may be deemed appropriate for the UK construction industry, but are unlikely to be the only, or the most appropriate, combination in other regional markets.

Unprecedented population growth continues to exacerbate the severe housing shortage in many developing countries. The provision of affordable housing is highly dependent on the availability of low-cost building materials. Given that choosing to build with locally available materials reduces importation costs, supports local economies and can reduce the environmental impact of construction (Morel et al., 2001); there is a strong case for the development of regional construction solutions. Low-cost cementitious binders are recognised to be essential for upgrading infrastructure systems and building secure, robust and durable housing.

Lime-pozzolan concretes with 28-day compressive strengths of around 50 MPa have been observed by utilising a ternary blend of SF and GGBS, both of which are industrial waste ashes and high valuable commodities. Such compressive strengths may be necessary in the delivery of high-density housing, but in many applications lower compressive strengths may be sufficient. Fly ash (FA) and metakaolin (MK) were omitted very early on in this research programme when their pozzolanic efficacy was surpassed by GGBS and SF. Having observed a substantial enhancement in mechanical properties of lime-pozzolan concretes in the second and third phases of testing, there is thought to be value in revisiting those pozzolanic minerals that were omitted immediately after phase 1. For example huge quantities of stockpiled FA make this pozzolanic mineral both a cost-effective and ecological resource. The results in Paper 1 have shown that the pozzolanic efficacy of FA (only) is 37% in but increases to more than 80% when utilised in ternary combination with SF. Other industrial waste ashes that may warrant further consideration in the development of future lime-pozzolan cements include paper sludge ash (Bai et al., 2003), sewage sludge ash (Cyr et al., 2007), municipal solid waste ash (Aubert et al., 2004) and oil shale ash (Smadi and Haddad, 2003, Gao et al., 2009).

Similarly MK, calcined clay, was omitted from the investigation after study 1. The results in paper 1 demonstrated that MK could be combined in ternary blends to complimentary effect, with MK shown to be beneficial in combination with GGBS and FA. The pozzolanic efficacy of ternary lime pozzolan binders based on SF and MK has not been studied to date. Calcined clays also have pozzolanic properties and warrant further study in the development of low-cost lime-pozzolan concretes due to their widespread availability.

Low-cost agro-wastes are also being investigated as partial CEMI replacement materials because of their pozzolanic properties. These materials might also warrant further investigation in the development of regional lime-pozzolan concretes: rice-husk ash (Chao-Lung et al., 2011), sugar cane bagasse (Cordeiro et al., 2008), saw dust ash (Elinwa and Mahmood, 2002), corn cob ash (Adesanya and Raheem, 2009), coconut husk ash (Ettu et al., 2013b), wheat straw ash (Biricik et al., 1999), locust bean pod ash (Adama and Jimoh, 2012), palm oil fuel ash (Tangchirapat et al., 2007), cassava waste ash (Ettu et al., 2013a), olive waste ash (Cruz-Yusta et al., 2011) and periwinkle, oyster and snail shell ash (Etuk et al., 2012).

Of this selection of waste ashes rice husk ash (RHA) is particularly interesting in the dialogue about future lime-pozzolan concretes, because of its wide scale availability and its high content of amorphous silica, which makes its oxide composition not dissimilar from that of SF. The pozzolanic properties of RHA are highly dependent on firing and grinding, but under carefully controlled conditions can result in a highly reactive pozzolanic mineral with an amorphous silica content of up to 95% and a large surface area (Chao-Lung et al., 2011). Rice husk is an inexpensive by-product of rice, the staple food crop of more than half of the global population (Nations, 2013). Rice husk ash (RHA) is a siliceous ash left behind after burning the rice husks (RH), which has long been the common means of disposing of this material. Approximately 50kg of RHA can be generated for every 1000kg of rice paddy milled. In 2010 700 million tonnes of rice paddy were milled (Food and Agriculture Organisation of the United Nations, 2013) suggesting that around 35 million tonnes of RHA was produced. This is substantially higher than the 640,000 tonnes of SF that was reported to have been produced worldwide in 2011 (China Microsilica Union, 2011). In 1977 highly reactive risk husk ash was observed to be 'excellent' for making both CEMI and lime-rice husk ash cements (Cook et al., 1977).

As well as artificial pozzolanic materials substantial deposits of naturally occurring pozzolanic materials have been identified. Known deposits are located in Italy (volcanic tuff), Germany (Rhenish Trass), Greece (Sanatorin Earth), Tenerife (Tosca), France, USA, Canada, Japan, New Zealand, Kenya, Tanzania, Rwanda and Indonesia (Holmes and Wingate, 1997).

Based on the results of laboratory testing of ternary lime-pozzolan concretes, there is substantial scope for broadening this field of enquiry into the testing and development of regional lime-pozzolan concretes that exploit locally available materials. Commenting on the Paper 1, the academic who peer reviewed this paper observed: *'The paper is interesting and* *the results allow to dream in lime-pozzolan concretes. Probably in developed countries will be a dream, but in developing countries that has a good quality and low cost pozzolans like rice husk ash, sugar cane ash, volcanic ashes....will be a reality.'*

Clearly it is essential that the quality and durability of regional lime-pozzolan concretes is not unduly compromised by the utilisation of alternative alumonosilicate materials. Further optimisation and an in-depth study of the reaction chemistry and microstructure of lime-pozzolan binders is anticipated will be beneficial in limiting the list of candidate pozzolanic mineral additions, and combinations thereof, and thus reducing the number of possible lime-pozzolan concretes.

13.4 Composite structural systems

Progress in the above three areas will create opportunities for lime-pozzolan concretes, to be utilised, as alternatives to Portland-cement concretes, in a number of composite construction systems. The value offered by composite building systems is a function of the nature and number of design requirements that the composite systems can provide synergistically. It is recognised that specification of lime-pozzolan concretes as part of a composite system, may be one way to absorb the initial premium cost.

One such composite system could be the development of timber-lime-pozzolan concrete composite floor decks. Timber-concrete composite (TCC) floor decks have been used in Europe, America and Australia but are a novel structural solution in the UK. TCC floors are recognised to be a low-CO_2 structural solution, with the concrete topping enhancing the dynamic, acoustic, thermal and fire performance of timber floors. In 2012 the dance studio in Thomas Clarkson Community College in Cambridgeshire became the first example of a CLT-concrete floor deck (Neve, 2011).

Some initial work has also been conducted on the performance of limecrete-timber composites, but the use of a limecrete topping with a relatively poor mechanical properties (typically compressive strengths of 10-12MPa) has demanded a substantial topping thickness (increasing the weight and embodied impact), limited the structural capacity of the overall system and put increased demands on the design of the fixings between the timber and the concrete (Hodsdon and Walker, 2006, Sebastian et al., 2010a, b).

The mechanical properties that have been observed in this investigation create opportunities for the substitution of CEM1 toppings with lime-pozzolan concrete toppings, to further reduce the embodied impact of this composite structural solution in the future. Given that the stiffness of ternary-lime pozzolan concretes has been observed to vary, and to deviate from that of CEMI (see paper 2) (Grist et al., 2014b), further testing is necessary to understand the required material stiffness in a composite floor deck. Due to the required compatibility in a composite system, development could either be led from the lime-pozzolan concrete technology end or alternatively a lime-pozzolan concrete could be designed to meet the performance criteria required by the composite system. For example the thickness of the topping might not necessarily be governed by the required structural capacity, but by the acoustic or thermal performance of the overall floor makeup. This could vary from project to project, in which case a detailed understanding of the mechanical characteristics of lime-pozzolan concretes, would be needed to be able to meet the requirements of a performance specification.

As part of a composite floor make up the lime-concrete topping might also be expected to provide the wearing surface and/or encase an underfloor heating system and. Although this research has shown that lime-pozzolan concretes can be polished (see Paper 8) (Grist et al., 2014a), further testing is needed to quantify the thermal performance of lime-pozzolan concretes and their slip, stain, chemical and wear resistance in use. Specifically the slip classification of floors is quantified by coefficient of friction (BS 7976:2002) and surface microroughness testing (performed using a roughness meter) (HSE, 2012). Chemical and wear resistance could have been evaluated in accordance with BS EN ISO 26987 (2012) and BS EN 13892-4 (2002) respectively.

Given that the results have demonstrated a reduced carbonation resistance in comparison to CEMI, there is scope for developing fibre-reinforced lime-pozzolan concretes, based on non-metallic fibres, to eliminate the risk of reinforcement corrosion. For example lime-pozzolan concretes reinforced with natural fibres, such as sisal, hemp and coir (Coutts, 2005) might warrant further investigation in the future development of this technology. In the case of the polished lime-pozzolan concrete floor screed (see Paper 8) (Grist et al., 2014a), it was observed that the steel reinforcing mesh accounted for 43% of the total embodied energy and 30% of the embodied CO_2 of the overall floor system. A natural fibre reinforced lime-pozzolan concrete thus has the potential to be both a more durable and significantly more ecological solution.

14 Concluding remarks

This strategic market analysis has highlighted a range of potential applications for this innovative concrete technology. It has also been effective in identifying a number of uncertainties about the performance of the novel concrete, which could form the basis of future work.

The use of NHL in conjunction with pozzolanic materials has been shown to be a viable 'low-CO_2' alternative to CEM1 or CEMIII/A in certain circumstances. Moreover the potential for lime-pozzolan concrete with a lower still CO_2 and energy intensity than any concretes tested to date has been noted.

As well as having been a vehicle for studying the implementation of sustainable construction materials, this materials research programme could prove to be a platform for future research and development on lime-pozzolan concretes. It is hoped that the research reported in this thesis will inspire and inform a number of subsequent research projects.

IMPLEMENTATION

Part B: Lime-pozzolan concrete

The story of a novel, low-CO_2 concrete
in the ‘real world’

15 Introduction to PART B: Implementation

In this practitioner research a real-world construction project was utilised as a vehicle for investigating the applied-innovation process. The aim of the research was to gain a deeper insight into how innovative and sustainable materials are evaluated, integrated and ultimately specified in construction design projects. A case-study research approach was adopted to gain a deeper understanding of the socio-technical complexity of implementation processes in construction. Focussing on the on the design process was anticipated to reveal opportunities to improve the effectiveness of similar project level processes, in order to increase the innovative capacity of the construction industry and to support the uptake of sustainable materials.

A case-study project was not sought out for this research programme; rather the research strategy emerged out of an opportunity to use this specific project as a case study for investigating this topic. This opportunistic research approach is characteristic of qualitative studies in which researchers often have to be prepared to ‘respond to unanticipated opportunities that arise in the course of the research’ (Miller et al., 2004).

In December 2010 Ramboll were appointed as the structural engineer on a new school building. The project brief expressed the school’s desire to utilise innovative and sustainable construction technologies and Ramboll were engaged as part of the design team to develop the scheme to RIBA stage D in line with the design brief.

The researcher was brought into the project team as a specialist materials consultant to support the design team in considering and adopting sustainable construction materials. This was recognised as a valuable opportunity to graft a research study onto a ‘live’ project in order to gain a deeper insight into the implementation of innovative and sustainable construction materials (Baszanger and Dodier, 2004). As a result the researcher was present in two discrete agencies, as consultant engineer and as a data gatherer.

15.1 Aims and objectives

The overall aim of the research was to identify opportunities to improve design processes in construction to support the uptake of innovation and sustainable solutions. To this end, theoretical insights were sought to inform the management of design processes in order to better enable and control desired outcomes. The objective of this process-tracing case-study research was to build empirically valid theories grounded in the real world project-level experience (Eisenhardt, 1989). A high degree of explanatory richness (George and Bennett, 2005) was sought in order to infer the best possible explanation for emergent design-outcome. Generalizable theories, which help explain the outcomes of current design practice, are recognised to be hugely valuable in designing future practises.

15.2 Research focus

This project-level case study focused on what Hartmann et al. (2006) describe as ‘the process that forms an attitude towards innovation and leads to the decision to implement a new idea’, which they suggest ‘has not been investigated in detail’. Based on the findings of Hartmann et al. (2006), this research focused on project-level communication, both written and oral.

Focusing on the design process was anticipated to reveal opportunities to improve the effectiveness of similar project processes in order to support the uptake of novel technologies in construction.

The aims of the academic research were explained to the design-team at the outset of the project and all those involved consented to this project being used as a case study for investigating the *implementation* process. The design-team was not however party to the research questions, so as to preclude any alteration of behaviour.

15.3 Literature Review

15.3.1 Design-process research

In this research, Benner and Tushman's (2003) definition of process, ‘a collection of activities that, taken together, produce outputs for customers’ has been adopted. The essence of a design-process being, more specifically: to narrow down the many options for meeting a client’s requirements to just one; a progressive reduction of uncertainty accompanied by a progressive increase in value (Winch, 2001).

Design-processes have typically been modelled linearly, with progression being understood as the step-wise completion of a series of distinct and consecutive stages (Zaltman et al., 1973; Drucker, 1999). Bucciarelli (1988) likened such, ‘design as a mechanical process’ to a ‘machine’.

More recently new management theories have emerged which have highlighted ‘the complex, paradoxical, interactive and self-organising features of organizational processes’ (Miller et al., 2004). Those that believe that human processes, including design and innovation, cannot be understood, or effectively managed, using step-wise linear models (Barrett and Sexton, 2006) subscribe the behavioural school of thought. Research in this area does not seek to construct generalizable models of organisational processes but rather seeks insights into what Strauss and Corbin (1990) describe as 'the unfolding nature of events'.

15.3.2 Construction design process research

Construction projects are generally recognised to be 'highly complex, uncertain and risk filled' contexts for design (Ivory, 2005) and the construction industry has been classified as a 'complex systems industry' (Winch, 2001). Design processes in the construction industry are typically project-level, client-focused processes resulting in bespoke, low-volume products (Winch, 200; Ivory, 2005).

In this context it is hardly surprising that innovation, and the extra complexity it inevitably introduces, is thought to be an unwelcome and 'highly vulnerable' addition to the design process (Ivory, 2005).

15.3.3 Innovation process research

Van de Ven (1986) described the innovation process as 'managing ideas into good currency'. Two basic processes that have been researched within the context of innovation are diffusion (Rogers, 2003) and adoption (Dewar and Dutton, 1986).

Diffusion of innovation concerns the spread of new idea and thus ultimately 'the impact of research on the economy and society' (Godin, 2006).

Adoption on the other hand concerns the decision to implement a novel technology and puts the emphasis on the adopter. Technology adoption has been extensively studied in the Information Technology (IT) industry, with a number of adoption models having been developed, including the Technology Acceptance Model (TAM) and the Unified Theory of Acceptance and Use of Technology (UTAUT) (Wells et al., 2010). In this domain attention has been given to user perceptions and the influence of cognitive and affective beliefs in influencing adoption behaviour (Agarwal and Prasad, 1998).

Social studies of science and technology, including Actor-Network Theory (ANT) (Callon, 1986; Latour, 2005), take a more holistic approach arguing that 'innovation processes should be studied as a simultaneous development of an artefact and a network of actors connected to it' (Miettinen, 1999).

15.3.4 Innovation processes in construction

Given that innovation creates opportunities to enhance performance, reduce environmental impact, reduce costs and secure competitive advantage (Hartmann et al., 2006) there is a great deal of interest in understanding innovation processes in the construction industry. Studies considering innovation processes in construction tend to have been conducted at one of three levels: innovation at an industry level (Winch, 1998), innovation at a project level (Connaughton et al., 1995) and innovation at a product level (Rasmussen and Shove, 1996).

Nam (1989) acknowledges that 'a great deal of empirical research dealing with causes and factors of success and failure in construction innovation is necessary to support theoretical assertions'.

15.3.5 Innovation as a human process

Agarwal and Prasad (1998) suggest that the process of innovation is 'characterized by complex behavioural and social phenomena'. Researchers subscribing to the behavioural school put people at the centre of innovation processes, or stories, as do systems thinkers. Some have focused on individuals, demonstrating the role of innovation champions (Nam and Tatum, 1997; Markham and Aiman-Smith, 2001; Howell and Boies, 2004) and highlighting differences in individuals' risk tolerance and propensity to innovate (Zuckerman and Kuhlman, 2000). Others concentrate not on the individual as the unit of analysis, but rather on the activity system, 'a community of actors who have a common object of activity' (Miettinen, 1999).

15.3.6 Innovation as a social process

It is recognised that engineering design is characteristically a social activity that ensues in a collective context. Research considering the primacy of social processes in innovation, has focused on what Ivory (2005) describes as 'the unique politics of each project's makeup'

A number of research projects studying innovation in a range of organisational contexts have focused on the 'collective action' of project teams (Slaughter, 2000) and highlighted the importance of actor-systems networks (Callon, 1986; Law, 1992; Harty, 2008). For example, Ivory (2005) posits that the innovation process in construction is 'a complex multi-actor activity that requires active consensus building in the context of divergent interests'.

15.3.7 Innovation as a process of interaction

It is recognised that the ‘communication characteristics within a social system’ strongly affect innovation (Mohr and Spekman, 1994; Agarwal and Prasad, 1998). Hartmann et al. (2006) go further concluding that ‘the innovation-adoption process of construction clients is first of all a communication process’. Bucciarelli (1988) describes the ‘design as effective communication’ viewpoint as a ‘management perspective’ on innovation.

15.4 Research approach

The research approach adopted in this study is qualitative and uses a case study project as a vehicle for investigating the implementation process. It is an example of what George and Bennett (2005) have labelled as a process-tracing case. Miller et al. (2004) have stressed that ‘Qualitative research has a particular part to play in exploring issues of process, in explaining how outcomes are achieved – or not as the case may be’. The use of case studies is advocated by Yin (2003) in the study of complex and context-sensitive phenomena, where other research methodologies are too broad to probe the details. Human activity systems, such as the undertakings of the design team in this case, are uniquely complex and contextual in nature (Miller et al., 2004)

Qualitative research is resolutely grounded in the specific context. This differentiates it from quantitative research, which demands phenomena to be both generalizable and representative. As Miller et al. (2004) have summarised this saying ‘in qualitative research context is stressed as opposed to stripped’. This inquiry cannot be, nor could have been, extricated from the context imposed by the doctoral research project, which engendered an atypical academic-industry relationship. It was exceptional for the industrial project team to have the advice and support of a research engineer specialising in sustainable construction materials, whom had access to university laboratory facilities for materials testing at no cost to the project. Equally, it is exceptional for the academic community to have access to the innermost workings of an industrial project.

Qualitative research findings contribute to what Lloyd (2000) describes as ‘an emergent understanding of a culture’. Akin to Glaser and Strauss' (2007) ‘Grounded Theory’ the research study largely forwent specific hypotheses, approaching the case study without assuming any prior knowledge or any one aspect of the data to be important (Miller et al., 2004). Rather the emphasis was on capturing what was actually said and observed and letting theories emerge from in-depth scrutiny of the data.

The micro-analytical research approach employed in this study aimed to explore how the minutia of talk is used to envisage, develop and negotiate possible future realities in the construction design process. It was much like both conversation and discourse analysis in this respect. The purposive nature of the conversation in this design process made the analysis more akin to discourse analysis, which focuses on the wilful, as opposed to sequential, organisation of language. Specifically this project considered the discourse around materials within a 'real-world' construction project, which provided a uniquely purposive transaction set (Winch, 2001).

The following six modes of interaction were identified as constituting the project-level interaction, through which the design team collaboratively formulated the design.

1) Design team meetings *(formal gatherings of project coalitions, typically chaired by a nominated individual and following an predefined agenda).*
2) Intra-organisation *(formal or informal conversations with one or more colleagues).*
3) Intra-project coaltion *(formal or informal conversations, typically between two actors from different organisations in the project coalition, often over the telephone).*
4) External *(formal or informal conversations with third party actors)*
5) Documentary communication (*written or electronic documents shared between individual actors, organisations or distributed across all or part of the design team).*
6) Shared models (*including sketches and 3D models).*

The focus was not on the language itself, as it might be in linguistics, but on 'language as the medium for interaction' (Potter, 2004). Discourse, including natural talk in conversations and written text in documents, is described as being 'rhetorical and orientated to action' (Potter, 2004).

This research approach was interactionalist in nature, starting with the belief that humans are uniquely purposeful and that language is one tool they wilfully use to 'create and maintain meaningful worlds' (Miller and Glassner, 2004). Looking at a project-level design process, it was pre-supposed that that the interactions, interpretations and actions of the project team were able to construct a both a new physical reality, in this case a new building, and a new social reality.

16 Methodology

16.1 Fieldwork

In this case study primary data was collected by producing audio-recordings of design team meetings. This data was supplemented by the collation of documentary records and field notes. In addition semi-structured interviews with individual member of the design team were conducted at specific junctures.

Data was collected over a period of eighteen months, which enabled socialization in the group and immersion in the subject. Making audio-recordings of design team meetings was ethnographic in approach, in that data collection was not orchestrated but gathered insitu in order to observe the endogenous progression of the design (Baszanger and Dodier, 2004). Being a member of the design team, in the capacity of an engineering consultant, inevitably led to the researcher becoming a participant-observer in the process. Fox (1994) describes participant-observation as 'the process by which the participant-gradually makes organized sense out of what he sees, hears and becomes part of '.

Because the researcher was a participant in the process being studied, it is appropriate to understand her stake in the process and to take this into account when interpreting the results of this study (Potter, 2004). In her agency as an engineering consultant, especially one present as a specialist in sustainable materials, it was the research engineer's responsibility to assist with the adoption of innovative and sustainable materials, in line with the client's brief. Accountable to the client, it was the *outcome* of the process that was important in this capacity. In her agency as an academic researcher the outcome of the process was unimportant; moreover the research engineer's responsibility was to ensure that the research study had minimal impact on the outcome. In this capacity, the research engineer was accountable to the academic community and the *process* was important.

This dual-agency demanded a great deal of hat swapping and care on the part of the research-engineer. For example it was inappropriate for her to act in any way as to alter the general course of the design process, except in fulfilling her role as a design consultant. As has been discussed the results cannot be stripped of this contextual detail, but notwithstanding great care was taken for the research engineer's participation not to affect the reliability of the results.

16.2 Analysis of the design team meetings

16.2.1 Data capture

Five consecutive design team meetings, spanning seven months, were recorded in-situ, promptly transcribed and then coded using a selective framework. The recordings were made on a dictaphone, which was placed in the centre of the table around which the design team meetings took place.

Transcription of the data stabilised the speech in written language, improving the accessibility of the information for subsequent analysis (Thorsten et al., 2012). It is recognised that it is impossible to fully represent human communication in written text and that transcription always involves a conscious compression of the recorded data (Skukauskaite, 2012). In this study the transcript produced after each meeting is acknowledged to be a sample of the collected data, representing only those sections of the conversation pertaining to directly or indirectly to the construction materials.

Given that the transcripts were to be coded based on semantic content, prosodic elements speech elements, such as volume, intonation, speed and pitch were omitted to enhance readability. Consentient vocal interjections, monosyllabic answers, hesitations, pauses and laughter were however all transcribed, as these elements helped characterise the natural modulation and tone of the discourse. Having been present in all the meetings that were recorded, it was also possible to transcribe where speakers gestured towards specific objects, which enhanced the comprehension of the written record.

The transcription style of the researcher developed over the course of the research project, a learning process that was aided by the acquisition of a play-back foot pedal and F5 audio transcription software from Audiotranskription, which automatically time-stamped each new line of speech.

16.2.2 Data handling

To protect the details of the project and individuals involved the transcripts were anonymised, using a simple search and replace method. The institutional role of each speaker was however maintained in the anonymisation of each actor, so that inter-personal and inter-organisation relationships between actors could be identified.

Anonymised actor codes are ‘ethnographic particulars’, which act as markers giving both the analyst and the reader a clue as to the status and goal of each speaker. The impact of this methodological decision is debated (Schegloff, 1997; Billig, 1999), as although it provides contextual relevance, it is also recognised to be characteristically deterministic, creating an opportunity for the analyst's prior assumptions to influence the analysis.

16.2.3 Data analysis

Each anonymised transcript was selectively coded (Glaser and Strauss, 2007) using a pre-defined analytical framework based on De Bono's (1999) 'Six Thinking Hats'. It is recognised that the practise of coding 'results in telling only parts of stories, rather than presenting them in their 'wholeness' (Miller and Glassner, 2004).

De Bono's (1999) 'Six Thinking Hats' is an organisational thinking tool, which claims to help users 'run better meetings and make faster decisions'. The tool is widely used around the world and anecdotal evidence suggests it is a highly effective decision-making tool, 'A researcher from a top IBM laboratory told me that the Six Hats method had reduced meeting times to a quarter of what they had been'. In this study De Bono's (1999) 'Six Thinking Hats' was employed as a classificatory framework for categorising the orientation/perspective of the speaker revealed in each utterance. Retrospective use of this tool as an analytical framework for studying natural, 'unstructured' decision-making processes is believed to be unique.

The analysis was performed having the 'Six Thinking Hats' framework on a cue card for easy reference (this is included in Appendix A). Other constitutive elements of the interaction that were identified during analysis of the transcript were heuristic markers such as mental models and metaphors.

In the light of the novelty of this analytical approach, long excerpts of the transcribed speech have been presented intact in the results, in order to allow the reader to evaluate both the reliability of the data and the analysts coding, an approach advocated by Sacks (1974) in (Silverman, 2004).

The analysis of the transcribed audio-recordings was similar to conversation analysis in that it focused 'on the way in which social realities and relationships are constituted through persons' talk-in-interaction' (Miller and Fox, 2004).

16.3 Analysis of the documentary records

It is suggested that documentary records, including written and electronic records, can be of 'pervasive significance' (Atkinson and Coffey, 2004) and therefore warrant close scrutiny in the analysis of collaborative design processes. Emails, reports, sketches, specifications are key examples of non-verbal communication in the construction design process, where face-to-face meetings between geographically dispersed parties can be infrequent.

16.3.1 Data capture

All project documentation pertaining to the innovative construction materials and received by the researcher, in her capacity as a member of the design team, were collated and scrutinised in this study. Collectively these documentary records 'constituted an archive of text that was vastly more accurate than human memory in the reconstruction of prior events' (Markam, 2004).

That said it is recognised that these records were inevitably incomplete, being only those consciously shared with the researcher in her capacity of a professional consultant. Intra-organisational, inter-project coalition and external communication is almost impossible to capture, although in some instances specific conversations were alluded to in the design team meetings.

In this study shared models including sketches and models have not been used as documentary evidence, as the progression of the design was deemed to be satisfactorily understood from the other data sources.

16.3.2 Data handling

The temporal nature of information exchanged between one or more actors, as evidenced in the dating or time stamping of documentary records, was considered important. Specifically the sequencing of documentary records was systematically considered and the temporal relationship between the documentary records and the design team meetings has been highlighted, where this is thought to contribute to the narrative. It is appreciated that in the same way that 'documents make sense because they have relationships to other documents' (Atkinson and Coffey, 2004), it is thought that documentary and conversational records make sense because of their interrelationships. Collectively these records reveal the dialogue that runs through the design process, as well as emphasising holes in the data. These records also provide insight into the constraints of the project programme, which also came to bare on the implementation process (Hartmann et al., 2006).

In the case of each piece of documentary evidence the author and reader(s) have been identified. This is because of the inherent intentionality of written communication that is assumed in an interactionist analysis (Atkinson and Coffey, 2004), which argues that written language is shaped by an awareness of the desired recipient(s).

Documentary analysis also included the analysis of field notes, which constituted detailed notes or memos written during, of immediately following, meetings or phone conversations that the researcher was party to, but could not record. This is secondary data and has been highlighted as such, wherever it has been drawn upon as evidence.

16.3.3 Data analysis

An Excel spreadsheet was found to be an effective way collating and ordering the documentary evidence. This method also provided a simple way of analysing the elapsed time period between subsequent records.

16.4 Analysis of interview data

This discourse analysis of the narrative was augmented by interviews with specific members of the design team, as is frequently the case (Miller and Fox, 2004). Semi-structured interviews were employed to gain an authentic insight into the lived-experience of individual members of the project team (Miller and Glassner, 2004), which were effective in fleshing out the story.

Interviews are good for probing the subjective experience of the research subjects, gaining closer, deeper, fuller picture of the project-specific story. Although individuals are not able to offer generalizable insights about the world, they can be used to shed light on project-specific experiences and to assist in the interpretation of the story as a whole. It was considered appropriate to ‘grant these points of view the culturally honoured status of reality’ as advocated by Miller and Glassner (2004).

It is a common problem that the experience that an interviewee is willing to share can be highly dependent on interviewer. Being a member of the project team and undertaking interviews twelve months into the project programme, is thought to have permitted a level of trust to have been established between the interviewee and the interviewer, which is anticipated to have fostered an increasingly candid disclosure (Miller and Glassner, 2004). Being a member of the design team, as opposed to outside researcher, the interviewer also possessed a deeper subjective understanding of the circumstances that the interviewees described, which is argued to support a more meaningful interpretation of the narratives (Miller and Glassner, 2004).

16.4.1 Capture of interview data

The starting questions in each case of each semi-structured interview varied slightly but were always pre-determined. The questions were open-ended to encourage a narrative account that would constitute a window into the interviewee's social world, with minimal 'guidance' or 'interruption' on the part of the interviewer (Miller and Glassner, 2004).

16.4.2 Handling of the interview data

The semi-structured interviews were recorded on a Dictaphone, or latterly on two separate recording devises, and then transcribed shortly after.

16.4.3 Analysis of the interview data

Interview transcripts were analysed line by line using open coding to elicit emergent themes grounded in the data (Strauss and Corbin, 1990). Collectively these themes provided evidence of the socio-complexity of implementation processes in construction. Evidencing the complexity of empirical reality does not however provide generalizable insights that are valuable in leveraging and designing future processes. Further analytical steps were necessary to elevate the conceptual level of the emergent themes in order to build generalizable theories from the data (Eisenhardt, 1989).

Each theme was first compared with extant literature from a variety of academic domains to evaluate the conceptual validity of the observed phenomena (George and Bennet, 2005). Looking at the empirical data from a range of perspectives was valuable in identifying fundamental constructs, which in turn highlighted emergent relationships between themes. Emergent relationships between the themes enhanced the generalizability of the results and thus also their usefulness. The analytical process of building theories from case-study data is effective in highlighting *'structures below the surface level, which are less observable but may have more explanatory power than those on the surface'* (Jackson, 2000). These structures below the surface level should not only be explanatory when looking back at the case-study data but also powerful in designing implementation processes going forward.

17 Introduction to the case study project

This project comprised the design of a new teaching and learning facility for a local authority secondary school and local community. In 2004 the school was awarded specialist Science College status as part of UK's Specialist Schools Programme.

With an emphasis on science and technology the new building comprised four new teaching classrooms; themed Earth, Water, Fire and Air (in response to a pupil consultation) and a large double-storey hub space, designed for large presentations, performances or as break-out space for group learning.

The building was to be more than a safe and healthy place for students at the school to study; it had to be an engaging and valuable learning tool in its own right.

The following points have been extracted from the Stage C report and capture the design philosophy of the project:

- Creating a space that staff and pupils are proud of and thus fosters a culture of respect for both place and people.
- Creating opportunities for the local community to use the school.
- Involving pupils in the design process and where appropriate in the construction.
- Minimising the impact of the construction in the natural environment.
- Demonstrating what can be achieved with resources available on site.
- Carefully choosing the materials for the fabric of the building.
- Expressing the structure, so it is evident how the building stands up and holds together.
- Exposing all the fixings and services.
- Realising an innovative solution, to inspire pupils to be creative and optimistic about what can be achieved.
- Future-proofing the building for the installation of the latest technologies as they emerge.

17.1 Construction materials

Three material technologies in this case were considered to have constituted the innovative and sustainable aspects of the design: cross-laminated timber, rammed earth and polished lime-pozzolan concrete. It is recognised that the degree of novelty of these three construction technologies cannot be objectively determined (Wells et al., 2010), but each was considered to be 'innovative' on this project being in varying degrees new to the project team (Zaltman et al., 1973). For an introduction to cross-laminated timber (CLT) and rammed earth see the design guides in Appendices B & C respectively. These two guides were produced as part of the research programme and form part of a series of similar guides, providing an introduction to a number of low-impact technologies. The project also included glulaminated timber, glass, steel and concrete although these materials were not expressly considered in this analysis.

Retrospectively this construction project was observed to be a fascinating case study as these three distinct material technologies; cross-laminated timber, rammed earth and lime-pozzolan concrete, were observed to be carried through the design process and represent product sub-case studies. CLT and rammed earth were adopted in the final design and are therefore specific examples of the complete and effective implementation process, whereas the lime-pozzolan concrete was omitted from the scheme at the contractor appointment stage. This material is thus an example of a terminated or ineffective implementation process. As a result this case study construction project provided empirical evidence of what Frambach and Schillewaert (2002) classify as the 'pre-adoption, adoption and non-adoption' of innovative and sustainable materials.

17.2 The cast

The actors in this case study comprise the project design team. The term 'design team' has been used in this study to remain consistent with the project's own terminology and should be noted to include the entire project coalition, including the client and the end user, in this case the Local Authority and representatives of the school respectively.

Actors and their abbreviated anonymisation codes are detailed in Table 33.

Table 33: Actors, their projects roles and anonymisation codes

Project role	Codified reference	Code
School end user/client	Senior Leadership Team (A)	SLT(A)
School end user/client	Senior Leadership Team (B)	SLT(B)
School end user	Teacher (A)	T(A)
School end user	Teacher (B)	T(B)
School end user	Teacher (C)	T(C)
Local Authority client	Local Authority (A)	LA(A)
Local Authority client	Local Authority (B)	LA(B)
Local Authority client	Local Authority (C)	LA(C)
Clients cost consultant (PQS)	Quantity surveyor (A)	QS(A)
Architect	Architect (A)	ARCH(A)
Architect	Architect (B)	ARCH(B)
Mechanical & electrical (M&E) consultant	M&E consultant (A)	M/E.ENG(A)
Acoustic consultant	Acoustic engineer (A)	A.ENG(A)
Structural engineering consultant	Structural engineer (A)	ST.ENG(A)
Structural engineering consultant	Structural engineer (B)	ST.ENG(B)
Structural engineering consultant	Structural engineer (C)	ST.ENG(C)
Main contractor	Main contractor (A)	M.CON(A)

Note choice of the word ‘actors’ to reference members of the design team, is consistent with Actor-Network Theory (ANT) (Callon, 1986; Latour 2005) and in no way implies that these individuals were trained in the art of make-believe, which would clearly invalidate the findings!

17.3 Overall project timescale

The anchor meeting, the first occasion at which the majority of the design met, was on the 7th January 2011. The researcher’s first involvement in the project was to give the project architect a tour of the structures laboratory at the University of Bath on the 8th February 2011. A year later, on the 17th February 2012, the design-team issued the tender documentation to the client at RIBA Stage D. The construction of the new building was completed in August 2013.

17.4 Further details

An account of this case study project, focused on the story of the lime-pozzolan concrete floor is presented in: Grist, E.R., Paine, K.A., Heath, A., Norman, J. and Pinder, H., (2013). *Innovative solutions please, as long as they have been demonstrated elsewhere*. Case Studies in Construction Materials. January 2014 (see Section 1: Paper 8).

18 Results and discussion

18.1 Analysis of the design team meetings: *Implementation* through conversation

This section presents the analysis of the series of six consecutive design team meetings that took place between the 1st March and 28th September 2011. The analysis focused on linguistic features of the design conversation, using De Bono's 'Six Thinking Hats' (De Bono, 1999) as selective-coding framework.

Each design team meeting is considered in turn and then general insights emerging from analysis of the data are outlined. Where temporal information has been pertinent to the story, data from the documentary analysis has been used to support the discourse analysis.

A quote thought to capture the essence of each design team meeting was selected from the data for each meeting's title.

18.1.1 DTM01: "We are imagining…" (1st March 2011)

18.1.1.1 Overview of DTM01

In DTM01 the structural engineer made suggestions as to possible sustainable building materials that could be used in the project, specifically: CLT, hempcrete, straw bales and rammed earth. The architect was observed to enjoy exploring the possibilities but ultimately to moderate the 'divergent' solution space, by considering the compatibility of each suggestion with a pre-existing vision of the design. The quantity surveyor expressed his unfamiliarity with the materials being discussed and asked a series of 'black hat' questions about their technical performance.

18.1.1.2 Discussion of DTM01

Field notes made during this design team meeting provided evidence of moderated-divergence. The structural engineer was observed to have offered up a number of material possibilities for the fabric of the building. Although the architect expressed that this idea-generating process was *'quite fun'* and *'really interesting'*, he was also observed to have been keen to constrain the possibilities, *'We need to bottom out the materials and not be considering too many.'* This demonstrated the architect's 'management of attention'. Simon (1991) suggests that 'attention is a major scarce resource…we cannot afford to attend to information simply because it is there'. The design process was divergent but the extent of the divergence was controlled by the architect.

The architect was observed to control the building design, using his imagined future schema, to constrain the possibilities and guide the design process. The absence of any noticeable conflict suggests that the design ideas that the structural engineer had brought to the conversation, were only tentative suggestions and that the architect's ownership of the design was accepted and/or welcomed.

Supporting a Kantian interpretation (Jackson, 2000) there was evidence to suggest that the architect used compatibility with a pre-existing schema (existing in the imagined future), to limit the possibilities he was willing to attend to, having commented, '*How to express the articulation between the two materials, earth and timber?'* Cross laminated-timber was observed to have already become a feature of this imagined future solution; rammed earth was of interest because of the possibility of 'articulating' earth with the timber. The use of straw bales on the other hand was thought to have threatened to disrupt, rather than potentially have complimented the schema, for it was almost immediately disregarded.

The quantity surveyor was open about his unfamiliarity with the sustainable materials being tabled in this meeting and his initial sense-making process was observed to constitute asking a series of 'black hat' questions about the technical performance of the materials.

[QS(A)]: *Are there problems with drying out?*
[QS(A)]: *Can you build straw bale in the winter? (Is the material available?)*
[QS(A)]: *What about future maintenance?*

18.1.2 DTM02: "I think that the texture is quite important really" (8th June 2011)

18.1.2.1 Overview of DTM02

Following excavation of a sample of site-won earth from the school, a number of rammed earth cylinders were brought along to DTM02. 'Unveiling' of the rammed earth was seen to become quite an event. The results of initial laboratory testing and the opportunity to see and feel the rammed earth cylinders encouraged the design team to begin evaluating the novel material. DTM02 provides insights into the collective sense-making and evaluation processes, which characterize 'transformation' in design (Jones, 1970).

18.1.2.2 Discussion of DTM02

This design team meeting took place approximately eight weeks after the project Site Investigation (SI), which had been conducted by a geotechnical engineer. In order to assess whether site material was suitable for construction of a rammed earth wall, the researcher had been present during the SI to take a sample of the soil.

During the excavation of a number of trial pits, within the footprint of the new building, a 300-700mm thick band of frost-shattered limestone had been encountered from approximately 0.2 metres below the surface. In the trial pit log this material was described as ‘loose becoming medium dense beige brown to mid-brown silty sandy GRAVEL and COBBLES of sub-angular oolitic limestone’ (SI report, April 2011). Having recognised that this naturally occurring site material might also potentially be suitable for use within the fabric of the new building, a sample of this frost-shattered oolitic limestone, passed through a 50mm screen, had also been bagged for testing in the laboratory.

Since the site investigation, laboratory testing had been undertaken at the University of Bath to assess the suitability of the site-won earth for rammed earth. Specifically, the particle size distribution, the Atterberg limits and linear shrinkage of the earth had been tested in accordance with the relevant British Standards. The results of this analysis are included in Appendix D. On the basis of these results a number of rammed earth sample cylinders (100mm in diameter and 200mm tall) had also been produced and these were taken along to the design team meeting, to show the design team, along with a graphical representation of the test results.

The material samples were observed to heighten anticipation around the possibility of utilising rammed earth and additional members of staff were invited to join the design team meeting for the ‘unveiling’ of the rammed earth.

Together with the laboratory results, the samples facilitated an evaluative assessment of the possible innovative technology. Evaluation is a distinctive feature of the ‘transformation’ process, which is purported to link divergent and convergent processes in design (Jones, 1970). Specifically, Jones (1970) suggests that the ‘transformation’ process includes, ‘pattern making, fixing of the brief, identification of critical variables, reorganisation of constraints, opportunity taking and judgement making’. Strong evidence of evaluative cognitive processes during this meeting implied that the design was now in this ‘transformation’ stage.

Human evaluation and judgement making is argued to be predicated on two cognitive systems, one intuitive (System 1) and one reasoned (System 2). These two cognitive processes have been described by Kahneman (2003), ‘The operations of System 1 are typically fast, automatic, effortless, associative, implicit and often emotionally charged whereas the operations of System 2 are slower, serial, effortful, more likely to be consciously monitored, and deliberately controlled’.

The initial description of the laboratory testing and the graphical presentation of the results would have called for a System 2, evidence-based, analytical evaluation of the innovative technology. It is thought that the interpretation of the results, offered by the researcher, would have been highly influential given that the audience was unfamiliar with the experimental testing and thus also the results. As Kahneman (2003) suggests 'people are not accustomed to thinking hard and are often content to trust a plausible judgement that quickly comes to mind', such as that of an 'expert'.

Subsequent unveiling of the samples is thought to have prompted a System 1, intuitive, evaluation of the technology. Certainly, sensory evaluation of the samples was observed to produce a predominantly 'red hat' response implying a fast and emotive evaluation of the innovative material. Unlike graphical test results, visual and sensory stimuli are thought to be 'highly accessible', quickly bringing to mind mental constructs that are influential in the evaluation process (Kahneman, 2003). The 'accessibility' of the feedback from sensory evaluation of materials made this a highly emancipatory evaluative procedure (Jackson, 2003), drawing individuals into the design and decision making process.

Individual's intuitive evaluation of the rammed earth samples was observed to be based on patterns, identifying similarities and differences with *a priori* references, *'I'm really surprised at the yellowness of it'* and *'It really looks like clay'*. Prospect theory, as a model of human decision making, argues that, 'perception is reference dependent. The perceived attributes of a focal stimulus reflect the contracts between that stimulus and a context of prior and concurrent stimuli' (Kahneman, 2003).

The comment 'it looks really like clay' was one example of the use of metaphor (technically a simile in this case) in expressing and exploring associated frames of reference. There were a large number of examples of metaphors (Semino, 2008), and mental models (Mathieu et al., 2000, Cannon-Bowers et al., 2001), having been used in this design team meeting to aid the group sense-making process (Seligman, 2006). Metaphorical comparisons, between novel and familiar technologies, were observed to be effective in communicating and comprehending differential properties.

Unveiling of the rammed earth cylinders and the evaluative 'red hat' utterances that immediately followed, rapidly led to a discussion about where the rammed earth could be used, implying an agreement in theory. The overall and relative appropriateness of this material technology was considered in a range of potential locations. The conversation was informed by attention to function and aesthetic in turn. Specifically, it was agreed that the texture of the rammed earth wall should describe the construction process (expressing the formwork and bolt holes), so as to maximise the educational value of the wall. The rammed earth wall was considered an investment and it was generally agreed that if it required any painting or rendering, for reasons of durability or reflectant light levels, that it was not worth doing.

Throughout this conversation one member of teaching staff was the voice of sceptical pragmatism, a stream of 'black hat' questions demonstrating that she was looking to be convinced about the practicality of a rammed earth wall. By the end of the dialogue her 'red hat' utterance *'it's exciting'* was thought to be evidence that she had been persuaded.

At the close of the design team meeting another member of teaching staff requested a sample of 'limecrete', saying she understood it was being used somewhere in the building. Both the architect and the structural engineer were quick to correct her, saying *'we might be' and 'it's still something we are working on'* respectively. The sample of frost-shattered oolitic limestone, that had been taken from the school during the SI, had been found suitably well graded for use as aggregate without any sieving. Four experimental lime-concrete cubes, utilizing the site-won limestone as all-in aggregate had been cast on the 13th May. Unlike the rammed earth samples, the lime-concrete samples were not taken along to DTM02, for being just shy of 28-days old the lime-concrete was still awaiting compressive strength testing.

18.1.3 DTM03: "So there are just something's we need to think about, perhaps in a bit more detail" (21st June 2011)

18.1.3.1 Overview of DTM03

In DTM03 the acoustic engineer called for a greater focus on design detailing, initiating convergence towards the final solution. The client's quantity surveyor tried to elicit 'sacrosanct' aspects of the design.

18.1.3.2 Discussion of DTM03

A conversation between the architect and the acoustic engineer a week before this design team meeting was thought to have transitioned the design process into the convergent phase. In the words of Jones (1970) from here on in 'the aim is to reduce the uncertainty as fast as possible – to help rule out alternatives, to reduce a range of options to a single chosen design as quickly and cheaply as can be managed'.

Evidence of design convergence was seen in the architect's comment *'So yeah, I think if we all speak during this next week to try and actually start to pin some of the bits down'* and the quantity surveyor's call to identify 'sacrosanct' aspects of the design.

The spine wall was no longer being considered as rammed earth, which was deemed to have been prohibitively costly, and structural lime-concrete was briefly considered as an alternative solution. The lime-concrete option was subsequently talked out of the picture on the basis that it would have had a detrimental impact on the construction sequence and therefore have undermined the programme benefits associated with the CLT. That said the dialogue between the quantity surveyor and the structural engineer during this meeting suggested that these programme benefits had yet to be quantified in the cost plan. The structural engineer was observed to 'sell' the innovative timber solution, supporting Ivory's (2005) identification of this role in construction innovation processes.

The rammed earth wall although not expressly described as 'sacrosanct' was moved to an alternative, smaller location suggesting this had indeed become what Ivory (2005) described as a 'cherished design concept'.

In the context of a conversation about the acoustic performance of the space, the architect was hesitant to express that he imagined the floor finish to be a screed. The need for acoustic panelling in the space, was thought to have threatened the implementation of the sustainable materials, for it was recognised that if these aspects of the design were going to be hidden that they might as well be downgraded to familiar alternatives. This reinforced the idea that 'observability' of the innovation is crucial.

18.1.4 DTM04: "Why are we discussing this? Because of the possibility of using it or are we going to use it, or are we not sure if we are going to use it?" (17th August 2011)

18.1.4.1 Overview of DTM04

Discussion of the rammed earth and lime-concrete was observed to be a low priority for the design team, which raised questions about the team's design intent to pursue these innovative aspects of the scheme. Lack of clarity about the design and the design intent was increasingly problematic. The need to extract further site aggregate from the school to enable further testing and development of the novel lime-concrete, demanded that design intent was secured. The design team confirmed that they were keen to pursue this novel solution, but the extraction of more aggregate was not actioned, falling off the end of the meeting that had overrun.

18.1.4.2 Discussion of DTM04

In this design team meeting the conversation about the use of rammed earth and lime-concrete was had at the close of the meeting during ‘any other business’. The conversation was initiated by a representative of the school, who queried why material samples had been brought along to the meeting if they weren’t to be discussed, or perhaps used? This implied that this aspect of the design was a low priority for the design team, which raised questions about design intent.

The main construct emerging from analysis of this meeting was the primacy of design intent in furthering innovation. The uncertainty associated with innovation-processes is not limited to unknowable future phenomena (the realization of benefits and technical feasibility) but also to ‘hard to know’ present phenomena, specifically to design intent. In the case of the novel lime-pozzolan, further testing and development was recognized to be necessary and this testing was dependent upon the extraction of additional site-won limestone. At this stage, uncertainty surrounding the technical feasibility of a polished lime-pozzolan concrete screed clearly prevented the decision to specify this innovative solution being made. However, a degree of design intent, to such an end, needed to be secured to unlock the next stage of the research process.

Design intent is intangible phenomena, distributed asymmetrically across the design team, due to the multiplicity of individual values, perspectives and interests. It is an emergent property of a human activity system, discerned through language and action. Uncertain design intent hinders innovation processes; rather design intent gathered up and expressed facilitates action. Design intent is compared to Slaughter (2000) ‘commitment to innovation’ in the conclusion of this study.

This data provided evidence of how ‘intentionality’ is communicated though language. The conversation opened with a call for clarification of design intent, *‘I need to know really whether we want to pursue…’* and there were several examples of individuals seeking clarification about various aspects of the design, including the utterance that was selected as the title of this meeting: *‘Why are we discussing this? Because of the possibility of using it or are we going to use it, or are we not sure if we are going to use it’.*

The following utterances were pulled out of a conversation about the implementation of the novel lime-pozzolan concrete. These utterances were selected to demonstrate how design intent, or a lack thereof, is communicated through language:

'Yes, it's a possibility (line 293)

'*we would like to use limecrete, somewhere, possibly' (line 298).*

'the other place is in the lower ground floor to have polished limecrete floors?….Which we would really like.. (lines 301-302) '

'*We obviously want to try and use interesting materials wherever possible throughout the whole building'* (line 318).

'*Because I'd like, like you, to see the natural materials used as much as we can, and we need to see what the cost of doing that is' (360-361).*

'Yeah I think we, it would be great to' (line 418)

'We would definitely like to explore the limecrete… the rammed earth - we will explore it'….(line 420)

'Red hat' utterances, which are emotionally charged, were thought to be a poor communicator of design intent. That said, the 'red hat' utterance '*We would definitely like to'* was markedly more resolute. Equally, the use of the past tense was seen to cast doubt on design intent, which is characteristically future orientated. For example the utterances, *'the place which we had looked at as a potential for the rammed earth had been between these two...between the earth classroom and the water classroom for a while'* and *'Yeah, we always talked about having limecrete floor in places'*, both suggested that these design options had since been eliminated from the speaker's thinking.

In this meeting, design intent, with respect to the lime-pozzolan concrete, was deemed to have been satisfactorily established in the architect's utterance: '*Yes, there has been a lot of research into it obviously, and it's also, I think it's really, it makes it … it's quite unique, I think if we could use the lime in as many places as we could, so in gabions or certainly in the groundworks or the landscaping and in the floor'.*

Intent is thought to initiate and sustain innovation processes. When intent is ill-formed implementation is perceived to be vulnerable and innovation processes can falter. In this design team meeting the implementation of the rammed earth was evidently perceived to be vulnerable, because a number of individuals felt the need speak out and champion its inclusion in the scheme. Notably a representative of the local authority defended the cost of the rammed earth wall, arguing, *'I thought when we looked at the rammed earth wall the cost per square metre wasn't that excessive'.*

Cost uncertainty was observed to a substantial threat to the novel aspects of the scheme at this juncture, because of the supremacy of the project budget *'Yes, it's a possibility, it's, it's very much [erm] depending on the cost plan'.* This was not due to a lack of unit-cost information, which was detailed in the cost plan, but due to a lack of understanding about the cost implications of various options, '*there is no reason why we can't say we'll… if we change that wall to rammed earth, [erm] what will be the increase in the cost plan. Because I don't think it will be huge'.* In this case the local authority client was averse to seeing the rammed earth wall ruled out on the basis of cost uncertainty and proposed that the cost implications were further investigated before a decision was made. The quantity surveyor was absent from this design team meeting and the meeting ended with a number of cost-related actions.

Though intent to pursue the lime-pozzolan concrete as a floor screed was thought to have been secured, this did not translate into an action to extract further limestone from the site. Failure to action this task is attributed the decision having fallen off the tail end of the design team meeting that had already overrun.

18.1.5 DTM05: "Yes, let's allow for that –that will be our option that we'll put at stage C" (31st August 2011)

18.1.5.1 Overview of DTM05

DTM05 was short and sweet. Consensus was reached about a number of aspects of the design and decisions were made. Grade D timber was deemed sufficient for the CLT frame, reducing the cost uncertainty. The local authority confirmed that they wanted the quantity surveyor to cost in the rammed earth partition wall. With an 'extra-over' allocated to the lime-concrete in the cost plan, a clear decision was made to pursue the bespoke lime-pozzolan concrete for a polished floor application. The local authority agreed to organize the extraction of additional limestone from the site to facilitate further material testing.

18.1.5.2 Discussion of DTM05

Despite the brevity of this meeting it was thought to be a significant milestone in the innovation story. A number of design decisions were made and the meeting was closed with a representative of the local authority saying, *'we all know what we're doing and we've got…figures in the cost plan'.*

Analysis of this design team meeting provided evidence of the relationship between the design and the cost plan. The action of 'costing' an aspect of the design into the cost plan was observed to be highly efficacious. This action was hard evidence of design intent.

The decision to scale-back the rammed earth wall, from the central spine wall to a partition wall between two classrooms, was confirmed. Though this decision had been made for reasons of cost and construction sequencing, it was acknowledged that the benefits of this non-load bearing application, out of the public area, were limited. A representative of the local authority commented, '*there is a desire to have it there at least to show a rammed earth wall as a …[erm], you know as an example of what you can do. I think we should cost that in'.* The client's decision to get the quantity surveyor to cost the rammed earth wall into the cost-plan is thought to have been significant in the ultimate implementation of this novel technology.

With respect to the CLT, the architect, who had evidently been to visit a supplier, was able to confirm that Grade D timber was sufficient. This information would have facilitated a more accurate assessment of the cost, and represented a possible cost saving.

Representatives from the local authority tried on three occasions to close the meeting before the conversation turned to the lime-pozzolan concrete.

In this decision-making phase of the design process, language was used to talk aspects of the design into and out of the scheme. The lime-pozzolan spine wall was observed to be talked out of the design; a string of 'black hat' dis-benefits offered one upon another. Whereas, the local authority, the architect and the quantity surveyor were observed to talk a polished lime-pozzolan concrete screed into the scheme, primarily on the basis of cost! The lime-pozzolan concrete screed was described as being cheaper than linoleum but more expensive than polished concrete: ARCH(A) '*Oh well the polished limecrete is pretty cheap, relatively because that's your finish isn't it. That's what… the cost per square metre seemed a lot lower than linoleum or something like that…but then – limecrete is going to be more expensive than concrete'.* In this case the additional cost, in comparison to polished concrete, was countered by provision of an allowance in the cost plan, '*There is an extra over the concrete, which I did allow for, so there is an extra over on the last cost plan I did.'* Once money had been allocated to this novel aspect of the scheme, the cost plan was seen to be effective in supporting innovation.

Having reached a clear decision to pursue the bespoke lime-pozzolan concrete for a polished floor application, the local authority were rather obliged to assist with the necessary extraction of further limestone from the site. The conversation was ended with the local authority having said '*Well if you tell us what then we'll get something organized'*.

18.1.6 DTM06: "If you can agree with the school where it's going to be…then I'll organize it" (September 28th 2012)

18.1.6.1 Overview of DTM06

The additional limestone had not yet been extracted. The local authority implied that the structural engineers needed to organize this exercise themselves. Through a negotiation a decision is reached and this exercise was actioned.

18.1.6.2 Discussion of DTM06

An emphasis on the project programme and impending deadlines was evidence that the project was in the latter stages of the design process.

Analysis of this design team meeting comprised the study of a single dialogue through which the excavation of additional site-won limestone was negotiated. Given that LA(B) was perceived to have agreed to organize this task at the previous DTM, a month before, it was perhaps revealing that this exercise still hadn't taken place.

Initially, the representative of the local authority suggested that the structural engineer needed to arrange the excavation of material via the school, '*you need to arrange…to come out dig a few holes somewhere'*. After a lengthy exchange about the nature and scope of this undertaking the local authority agreed to organise a contractor to come and perform this task, '*we'll (.) if you can agree with the school where it's going to be…and the size of the hole. I'll get someone to price, give me a quick price and then I'll order it up, for them to come up and do it at a time to suit*'. The excavation of additional site-won aggregate, which was conducted on the 13th August 2011, unlocked a further phase of laboratory testing and development. The local authority's support, in enabling further research, was implicitly deemed to signify their commitment to the research angle of the project.

18.2 Conclusions of the design team meeting analysis

- Analysis of these six design team meetings has provided evidence of the design team going through the divergence, transformation and convergence that Jones (1970) suggests is characteristic of design processes. A parallel process was the transition of influence that was seen to move from the architect, to the budget and to the programme in turn.

- De Bono's 'Six thinking hats' (1999) was found to be an effective analytical framework and a valuable tool in this case. A study of the natural conversation used in this 'real-world' design process is argued to have revealed a number of features of language.
- Metaphors are used in design to grasp unfamiliar ideas (see DTM02).
- Language can provide insights into heuristic decision-making processes in design (see DTM02).
- Language communicates and influences creative energy. The sequence of 'hats' in a turn-taking dialogue has been seen to affect the energy level in a room. Alternating 'green' and 'yellow' hat sequences builds the energy levels up, whereas 'black' hat utterances bring the energy levels down (see DTM02).
- Language steers the process. Specifically 'black hat' utterances were seen to be necessary in driving the design forward by helping to convergence on a solution (see DTM03).
- Uncertainty in design processes is dispelled or aggravated by language. Specifically consider the communication of design intent in DTM04.
- Language is used to talk-in and talk-out aspects of the design (see DTM05).
- Negotiation is a powerful tool in design processes (see DTM06).

18.3 Documentary analysis and discussion: *Implementation* through written communication

Considering the written content, the sequencing and the temporal relationship between the documentary records and the design team meetings, shed light on three particular aspects of the design:

- The delay introduced in to the testing programme by the requirement to extract additional site-won limestone.
- Events between the last analysed Design Team Meeting (28th Sept 2011) and the issue of Stage D project documentation (17th February 2012) to the client.
- The concentration of communication immediately preceding the decision to omit the lime-pozzolan concrete from the scheme (15th March 2012).

Only the first of these three observations has been expounded in the case of this research project. This aspect of the case-study story is thought to be worthy of express consideration as it cuts across the somewhat artificial research scenario created by the collaborative EngD research programme. The vast majority of the materials' testing, undertaken by the researcher in the University laboratory, was conducted at no cost to the client as part of the doctoral research. However, the excavation of additional frost-shattered oolitic limestone from the school grounds, part way through the research process, demanded some financial outlay in support of the research process.

18.3.1 Results

A small sample of frost-shattered oolitic limestone (FSOL) was taken from the school on the 14th April 2011 during the project Site Investigation (SI). On the understanding that the school wanted to utilise site-won materials in the fabric of this building, the band of FSOL seemed promising and a sample was taken somewhat opportunistically. An approximately 25 kg sample of FSOL was enough to assess the particle size distribution of the sample and cast a handful of experimental lime-concrete cubes, but in reality little else. Four months down the line, this presented a problem. The design-team, inspired by the possibility of using the site-won FSOL as aggregate in a novel lime-pozzolan concrete, confirmed that they wanted to pursue the testing.

The need for further aggregate to enable further testing was first voiced to the design team on the 17th August 2011, during the design team meeting:

[ST.ENG (C)]: '*One of the things that we could look at, by way of doing more testing, would be whether crushing the aggregate, to a more uniform size, might help, with {reducing some of the surface cracking}.[Erm] <u>the problem that we've got is that we don't have any more aggregate at the moment, without digging another hole to get some out of the ground. So...that...so if we do want to do further testing, then that is what would be involved</u>… These samples here are the limit of what we've got using the onsite aggregate' (lines 196-202).*

This initiated a lengthy conversation about the intent to utilise the novel limecrete in the building, which concluded with the ARCH(A) saying,

'<u>We would definitely like to explore the limecrete</u>… <u>the rammed earth - we will explore it</u>…'(line 420-421).

The intention to continuing exploring the limecrete, particularly with the site-won limestone as aggregate, was reinforced in the dialogue between ARCH(A) and ST.ENG(A) in lines 472-477:

[ARCH(A)]: *<u>Well we I think we are going to explore it, we would like to</u>*
[ST.ENG (A)]: *<u>Okay</u>*
[ARCH(A)]: *Yes, there has been a lot of research into it obviously, and it's also, I think it's really, it makes it … it's quite unique, I think if we could use the lime in as many places as we could, so in gabions or certainly in the groundworks or the landscaping and in the floor*
[ST.ENG (A)]: *And with this aggregate where possible?*
[ARCH(A)]: *Yeah*

Although the local authority were not vocal in this dialogue, LA(A) rounded off the meeting by suggesting that ARCH(A) marked up a drawing showing both the rammed earth and the lime-concrete so these aspects of the design could be costed. Intent to pursue the lime-pozzolan concrete was perceived to have been secured in this meeting; however this did not translate into an action to extract further limestone from the site. This was attributed to the fact that this conversation had rather fallen off the end of the design team meeting which had on this occasion had overrun. The conversation was instead picked up at the next design team meeting a fortnight later.

In this design team meeting, on 31st August 2011, a conversation between the local authority, the quantity surveyor and the architect confirmed their intention to put a polished lime-concrete floor (with FSOL aggregate) in as their preferred option at RIBA Stage C.

[QS(A)]: *<u>I tend to agree</u>, I would have thought that we should go for something we are familiar with and can get up quickly for the spine wall and keep the limecrete for the floor and then polish it as we said.*
[ARCH(A)]: *<u>Especially if we can</u> use some of the aggregate like we saw last time – that looked amazing. Really nice.*
[LA(B)]: *<u>Yes, let's allow for that – and we'll cost that in the cost plan, and that will be our option that we'll put at stage C.</u>*
[ARCH(A)]: *<u>[Um um]</u>*
[LA(B)]: *<u>okay</u>*

The technical feasibility of this innovative solution was unknown and ST.ENG (A) reiterated the need to excavate some additional material to enable further testing, '*If that is something we are taking forward <u>we need to action getting some more material for testing'</u>* (lines 179-180). This prompted a lengthy discussion about what was involved in this task, which concluded in lines (214-219):

[ST.ENG (A)]: *I think you'd need an excavator.*
[LA(B)]: *<u>Well if you say what you want, quantity wise and we'll organize it.</u>*
[ST.ENG (C)]: *okay*

[LA(B)]: *some when, doesn't matter where does it – it's anywhere on the site*
[ST.ENG (C)]: *Yeah I think it was all very similar everywhere that we tested.*
[LA(B)]: <u>*Well if you tell us what then we'll get something organized.*</u>

On the 9th September, ST.ENG(A) emailed the LA(A) & LA(B), outlining the proposed testing, the amount of additional FSOL limestone required and emphasising that the results of the testing would take five to six weeks after receipt of the material.

"Following on from our conversation at the design team meeting, we have put together a programme of testing for the School limecrete – designed to use limestone dug from the site as aggregate. Although the tests to date have demonstrated an adequate strength, the viscosity of the mix has been too stiff. The workability is expected to be significantly improved by excluding the fine silty material, previously included as part of the all-in aggregate from the site.... We propose producing 9 batches, and systematically varying the proportions of water, lime and superplasticiser in the mix to investigate the effect on workability and strength....Having spoken with ARCH (A), we also propose to cast 3no. 400x400x60mm limecrete slabs, which they can arrange to have polished to assess the surface finish options. The production of these test cubes and slabs will require approximately 125kg of the limecrete aggregate. As only aggregate between 10-20mm will be suitable for inclusion in the limecrete the total material dug out of the ground will need to be considerably more that this...we estimate 500kg of material in total will need to be taken from site...The results of the consistence and strength testing will be available five to six weeks after receipt of the material. <u>Please could you confirm that you wish for us to go ahead with this further testing and that you are happy to make arrangements with the school for sourcing the material?</u> Once you have an approximate date in mind then we can confirm the arrangements for the delivery to the university."

Asking for confirmation that they wished to go ahead, the ball was put into the client's court. On the 15th September ST.ENG (C) emailed LA(A) & LA(B) following up their decision on the excavation of further site limestone.

"Further to ST.ENG (A)'s email below, we have drawn up a programme for testing of the {school} Limecrete (see attached). The testing will take some time because there are a lot of samples to create and it is necessary to allow adequate curing time. Working backwards from an assumed deadline of 10th November for production of engineering information for Tender (to allow the QS a further 2 weeks after we have issued all of our information) we

would need to be making a start towards the end of next week. Please could you advise whether it will be possible to obtain the aggregate from site in this time frame?"

Again on the 23rd September ST.ENG (C) emailed LA(A) & LA(B) chasing their decision on the excavation of further site limestone.

"In particular the limecrete testing has a long programme and ideally we should already have begun, however this is reliant on obtaining further aggregate from site. Please could you advise on this as mentioned in my previous email?"

There was no further communication about the lime-concrete testing until the design team meeting on the 28th September. At the end of the meeting LA(B) called for any further items to discuss, opening a further conversation about the excavation of additional FSOL.

[LA(B)]: *Okay, anyone anything else…*
[ST.ENG (A)]: *LA(B) we talked about getting some material*
[LA(B)]: *We did ...Yeah heah*
[ST.ENG (A)]: *…to do the limecrete testing.*

The dialogue that followed has been analysed in detail in DTM06, but was seen to be a negotiation though which LA(B) went from saying,

'*you need to arrange…to come out dig a few holes somewhere'* (line 34) to ' *if you can agree with the school where it's going to be…and the size of the hole. I'll get someone to price, give me a quick price and then I'll order it up, for them to come up and do it at a time to suit'* (lines 71-73).

Two-days later, having agreed a suitable location for the excavation with the school, ST.ENG(A) emailed LA(B):

"Following on from our conversation at the design team meeting, we have put together a method statement for sampling the School site limestone – for production of limecrete in the lab. The school have confirmed that the proposed location is suitable and are happy for the work to take place as soon as can be arranged."

The excavation of the lime-concrete took place on the 26th October (see Figure 31). The job required two contractors and an excavator. A hippo bag (approximately half a tonne) of site-won limestone, screened through a 50mm mesh, was sampled and delivered to the University laboratory, unlocking a further phase of testing.

Figure 31: Excavation of site-won limestone

18.3.2 Discussion

The requirement for additional aggregate was first flagged on the 17th August as 'gateway task' that for a number of reasons was not effectuated until the 26th October. This was thought to have introduced a two-month delay into the concurrent research and development process. An extra eight-weeks would ostensibly have allowed additional testing to have been conducted prior to the tender issue in February. That said, no additional testing was discussed between the 26th January when the polished lime-concrete samples were shown to the design-team and the 17th February when the polished lime-concrete floor specification was issued to the client as part of the tender documentation.

When the novel lime-concrete floor specification was omitted from the tender documentation in late February 2012, the lack of proof for the performance of this innovative floor solution was expressed as the primary concern. Further substantiation of the design was prevented by the project programme, or more accurately by the procurement route, as in reality the floor of the building was not laid for a further sixteen months.

The lack of response from the client to the three emails sent by the structural engineers between the 9th and the 23rd of September raises an interesting question in this case. Should ST.ENG(A) and ST.ENG(B) have interpreted the absence of a response as an indication of the client’s lack of intent to implement the bespoke lime-pozzolan concrete, and terminated the research or have persisted in the face of this ‘setback’? Certainly, it may have been beneficial to question the client on their silence and establish whether or not this delay was a cause for concern. This is an empirical example of timing, or more specifically response timing, being a marker of intentionality.

Events occurring between the last analysed design team meeting (DTM06) and the issue of the tender documentation at the end of Stage D were primarily captured in the documentary data. Analysis of this data showed a huge increase in the frequency of communication preceding the client’s decision to request the withdrawal of lime-concrete. This data provided evidence of the design team’s attempt to qualify the degree of novelty of this solution and to resolve issues of design liability.

18.4 Analysis of the interview data: *Implementation* from a first person perspective

A total of twenty-five themes emerged from line by line analysis of the interview transcripts. These themes, which were grounded in the empirical data, helped deconstruct the case-specific story. Comparison with extant literature was valuable in challenging the conceptual validity (George and Bennett, 2005) of these themes and highlighting relationships between them.

These themes are discussed in turn, but have been grouped and ordered with respect to the twelve theories that they collectively elucidated. These theories also build on the results of the design team meeting and documentary analysis, so henceforth the results emerging from the three strands of the enquiry are interwoven.

Table 34 summaries the twelve emergent theories, the twenty-five empirical constructs on which were built and the source(s) of the empirical data in each instance.

Table 34: Emergent theories and empirical constructs on which they're grounded

	Emergent theory	Supporting empirical constructs	Source(s) of empirical data
6.3.1	**Implementation is a phenomenological process**	***The experiential nature of applied-innovation as revealed by narrative accounts (6.3.1.1)***	*Interview analysis*
		The implementation process as a cached experience (6.3.1.2)	*Interview analysis*
		Existentialism (6.3.1.3)	*Interview analysis*
6.3.2	**Implementation processes are guided by individual heuristics**	***Interpretive flexibility (6.3.2.1)***	*Interview analysis*
		Mental models (6.3.2.2)	*Interview analysis*
		Cognitive prospection(6.3.2.3)	*Interview analysis*
		Creative confidence and problem solving (6.3.2.4)	*Interview analysis*
		Perceived degree of novelty (6.3.2.5)	*Interview analysis*
6.3.3	**Implementation processes are guided by 'affective' decision-making**	***Visual attractiveness (6.3.3.1)***	*Interview & DTM analysis*
		Observability of the innovation (6.3.3.2)	*Interview & DTM analysis*
		Observability of the innovation story (6.3.3.3)	*Interview analysis*
		Sensory evaluation (6.3.3.4)	*Interview & DTM analysis*
		Perceived risk (6.3.3.5)	*Interview & DTM analysis*
6.3.4	**Implementation is a social process**	***Social contagion (6.3.4.1)***	*Interview analysis*
		Interessement (6.3.4.2)	*Interview analysis*
6.3.5	**Implementation processes are contextually embedded**	***School specific context (6.3.5.1)***	*Interview analysis*
		Durability performance (6.3.5.2)	*Interview analysis*
		Risk assignment (6.3.5.3)	*Interview and documentary analysis*
		Procurement route (6.3.5.4)	*Interview analysis*
6.3.6	**Implementation processes are initiated**	***Technology coupling (6.3.6.1)***	*Interview & DTM analysis*
		Embodiment of the design philosophy (6.3.6.2)	*Interview analysis*
		Representation (6.3.6.3)	*Interview analysis*
6.3.7	**Implementation is predicated on human action**	***Part client and agency (6.3.7.1)***	*Interview analysis*
6.3.8	**Implementation is an interactive process**		*DTM analysis*
6.3.9	**Implementation is a temporal process of human activity**	***Opportunity grasping (6.3.9.1)***	*DTM and documentary analysis*
6.3.10	**Language, action and response-time are markers of intentionality in human processes**		*DTM analysis*
6.3.11	**Action and intention are mutually constituted**		*DTM and documentary analysis*
6.3.12	**Implementation is a mutually constituted process**	***Helplessness versus resilience(6.3.12.1)***	*Interview analysis*

Certainly there is considerable evidence in this case study to support Isaksen et al.'s (2011) argument that ‘people are key in implementing all change efforts’. The first three constructs speak directly into applied-innovation as a human process and help to expound why and how human actors play a key role in applied-innovation processes.

18.4.1 Theory 1: Implementation is a phenomenological process

What emerged from the lived-experience of the researcher, through rigorous analysis of a ‘real-world’ case study, was the primacy, and potency, of the conscious experience of human actors in the system; actors that shaped, and were simultaneously shaped by, the applied-innovation process (see Theory 12).

The forbearer of Phenomenology, Edmund Husserl (1859-1938), defined it as “the science of the essence of consciousness” (Smith, 2013). Phenomenology is the branch of philosophy concerned with the experiential nature of human consciousness and endeavour from a first person-perspective (Smith, 2013).

18.4.1.1 The experiential nature of applied-innovation as revealed by narrative accounts

During their interviews both SLT(A) and SLT(B) spoke about their excitement at seeing the lime-concrete sample panels for the first time, suggesting that this was a thrilling experience.

SLT(A) commented, ‘*I just remember very significant excitement about when we had the samples, when we were down in* (the local authority office)*. ...whatever it’s called. Those samples came round and I can only just say about the kind of physical excitement of seeing something that came out of our ground turn into something so [erm]...physical I suppose.’* (lines 8-11). Going on to say in lines 82-85, *‘Just really interesting the excitement you know when the rock samples..., SLT(B) with the earth for example, just the pure excitement that can come, the surprising excitement at the limecrete, very surprising that inanimate objects could bring around such physical responses and that’s just fascinating.’*

The ‘unveiling’ of the polished lime-concrete samples at the local authority office, is observed to have been similarly exciting experience for SLT(B), who is recorded to have said, *‘when you were at the office down town and you brought those samples along, erm you know those meetings tend to be a bit dull really, but that was a really exciting occasion and SLT(A) and I were just like wow - ...so that is when it became really exciting for me, that I thought actually yeah, this is really <u>really</u> great’* (lines 39-41 & 43-45).

Further examples of the experiential nature of the innovation process in this project are presented below:

Talking about the prospect of the CLT and the rammed earth wall the main-contractor, M.CON(A), also communicates his excitement, '*Well I am looking forward to the CLT as well…but yeah - the CLT structure I am looking forward to. Rammed earth wall(.) I am really looking forward to meeting RA.CON(B), because he sounds like someone off a Fosters advert. So I think that could be good'* (lines 517, 522-525).

Talking specifically about the rammed earth wall M.CON(A) is recorded to have said '*And this* (rammed earth wall) *is actually quite colourful really. So much stuff in building isn't very colourful, but it is a little injection of colour'* (lines 421-423).

Descriptions of events from a first-person perspective incorporating adjectives, such as exciting, interesting, fascinating, dull, great and colourful, emphasise the experiential nature of human existence Positive experiences, whether belonging to the past, present and/or the imagined future (*I am really looking forward to...),* are purported to be highly motivational in enabling innovation. A further example of the motivational nature of human experience from this case-study is 'interest'.

The efficacy of 'interest' is evidenced in a conversation had with the specialist polishing contractor, SS.CON(A), who asserted '*I'll have a go at anything really. Especially if it is interesting. That is the most important thing'* (line 331). This comment provides evidence of the link between perceived interest and a willingness to innovate (Wells et al., 2010). This relationship is thought to stem from mankind's inherent curiosity or 'epistemic interest' (Prenzel, 1992) and the 'functional significance' of interest in intellectual development' has been well documented (Dai & Sternberg, 2004).

The link between interest and a willingness to innovate is also recognised to resonate with Heidegger's post-modern philosophy. Heidegger argued that the drive for technological change is sustained by 'profound boredom', which he 'insists has become the pervasive and dominant mood of our times' (Thiele, 1997).

As well as describing experiential aspects of the applied-innovation process, interviewees were observed to reflect on the overall process in terms of it having been 'an experience'. In this instance experience reveals the reflective nature of human consciousness.

18.4.1.2 The implementation process as a cached experience

It was observed that many of those involved reflected on the implementation of sustainable materials, or attempted implementation in the case of the lime-concrete, as a fascinating experience.

SLT(A) expresses her desire to make the most of this 'experience', which she acknowledges in lines 43-45 as unique, *'a unique experience actually, because I think if you hadn't been studying this, probably wouldn't have had that, same with the earth and various other things like that. We wouldn't have had any of those experiences'.*

Similarly, for LA(A) this experience created the opportunity to gain an insight into her colleague's viewpoint, [LA(A)]: '*It's disappointing but [erm], I think it was right to point out the risks and that it is quite interesting from my point of view to see LA(C)'s side of it and er ...and the discussions that we had'* (lines 16-17). Looking at a situation from another individual's perspective is a cognitive mechanism called the 'theory of mind' (Schacter et al., 2007).

The main contractor speaking about his personal experience of implementing CLT on this scheme for the first time, similarly emphasises the value of this learning process, [M.CON(A)]: *'Well the CLT (.) we have done some timber frame projects before, not CLT, but in a way that became relatively easy, <u>the design development has been a pain, but (.) quite interesting pain really'.</u>*

This empirical evidence highlights a level of interest in the process, which is perhaps evaluated separately from the outcome.

The third construct contributing to a high level discussion of the nature of human experience is existentialism.

18.4.1.3 Existentialism

Existentialism cuts to the heart of human existence and endeavour. There are a number of utterances that provide evidence of SLT(A)'s desire for 'being part of' or 'being involved in' a bigger story.

[SLT(A)]: *<u>'for somebody like me who isn't involved in any of this world</u> to see it formulate into that <u>de-dah moment</u> was just, oh it was really really exciting* (lines 16-17).

[SLT(A)]: *'just being part of....from our ground, through innovation, through people working together and exploring, here is this sort of flooring… so then I felt equally crushed when it felt like the limecrete wasn't going to go anywhere in our own small project.'* (lines 20-21)

[SLT(A)]: *'that was a really interesting thing to be involved in, how can we achieve that kind of feel and look, what is the elements that was really exciting'* (lines 26-27).

[SLT(A)]: *'I was very excited that we could be part of something being developed and new'* (line 39).

[SLT(B)]: *'I don't know but it is that feeling of we are part of this thing, this building comes out of this environment that we are in, and that I suppose in a way that I had to compromise over that.'* (lines 121-123).

These utterances resonate with what Florman (1994) describes as the 'existential pleasures of engineering'. Florman (1994) argues that engineering is an existential activity that combines mans' 'primitive materialism', as described by Homer and writers of the Old Testament, and 'the existential impulse to change the world'.

Existential notions were not limited to SLT(A) for when the novel lime-pozzolan concrete floor was omitted from the design, a number of the design team were seen to take comfort in the belief that the technological story would continue regardless:

[SLT(A)]: *'how do we then make the most of that experience and that story and also just trusting the bigger journey you're making with the product, it's lovely to know that* (the school) *had a part of that, and that wherever it goes next – there is always a little bit of* (the school) *in there, as part of that learning journey'* (lines 41-44).

[SLT(B)]: *'But when ST.ENG (C) said to me you know, oh well we are going to us it in a roof construction, I thought wow-that is amazing, you know so it will happen sometime or another'* (lines 121-123).

[SLT(B)]: *'I want to think of this in my head that something will go on out of this that in the future, we learn from it, we move on, you know – that things will happen at Ramboll, and that they will have more confidence in pushing it forward and that other people will use it, you know, it will get there – but for us if it didn't it – you've just got to try and take that bigger picture, you know – where it will all end up I suppose.'* (lines 163-167).

Florman (1994) posits *'For the engineer, however, as opposed to the scientist, the fullest gratification is reserved for that creative solution which achieves a desired practical result'.*

Omission of the lime-concrete floor ostensibly denied the whole design team the opportunity of the existential gratification of implementing this novel engineering solution.

18.4.1.4 Implications of implementation as a phenomenological process

To a sociologist it may have been foreseeable that a micro-sociological research approach would expose the phenomenological complexity of engineering design processes. In fact the emergence of such a conclusion was perhaps likely given the use of interviews, which are inherently phenomenological in probing empirical reality from a first-person perspective. However, to an engineer, certainly to myself, insights into unconscious human processes, have been largely alien and have added a previously subliminal layer of detail to the engineering design process.

The phenomenological nature of innovation processes underpins the general model of ‘Innovation Work’ described by Böhle et al, (2012a) and thus this theoretical revelation opens up a body of management studies for further consideration by the construction industry. An experience-based approach to management is one of the three cornerstones of the ‘Innovation Work’ framework. Böhle et al, (2012a) also makes the distinction between the two forms of human experience identified in this study, writing ‘experience does not primarily refer to experience acquired in the past in the sense of one’s cache of experience, but to the actual process of experiencing and acquiring experience in the active process and resulting from taking action’.

Reading on it will become apparent that the vast majority of the constructs that emerged from the case study data fell under the umbrella of phenomenology, including: visual attractiveness, sensory evaluation, perception, representation and the significance of objects. Furthermore, the domain of phenomenology encompasses many of the other findings including human experience of the flow of time, social interaction, linguistic activity (meaning, communication and understanding others), action, collective action and the contextual aspects of intentional activities. Given the number of empirical constructs that this theoretical idea encompasses, it is thought that this is most persuasive and potentially the most valuable insight of the study. Espousing the value of experience in the context of innovation Böhle et al, (2012a) posit ‘Innovation work requires one has a special sense for yet unknown and not yet realized, but at the same time plausible results and approaches’ going on to say ‘such notion’s do not come from one’s imagination, but are based on experience’.

It is thought that an increased consciousness of phenomenology and its influence on human behaviour in engineering design could prove valuable in developing tools and processes to enable implementation and leverage project outcomes. Being able to explore why one thinks or feels a certain a way about something and how that affects ones actions, and to help others do similarly, could be beneficial in helping to filter human experience for salient insight.

It was acknowledged in the literature review that the process of innovation is 'characterized as a complex behavioural and social phenomenon' (Agarwal and Prasad, 1998). This is thought to be rooted in the fact that applied innovation processes entail judgement, decision-making and action under uncertainty. As a result theories of human judgement and decision-making are considered to be informative in implementation processes

Theories 2, 3 and 4 reflect the behavioural and social dimensions of innovation as a human process. The second and third theories focus on human experience and decision making at the level of an individual actor, speaking into the behavioural dimension of innovation and the fourth theory focuses on the influence of social phenomena. Specifically, theory 2 centres on individual cognition and theory 3 on individual emotion or 'affect'.

18.4.2 Theory 2: Implementation processes are guided by individual heuristics

Cognitive processes, including intention and hermeneutics - 'the art of interpretation in context' (Smith, 2013), are typically unconscious and in 'real-life' rarely made explicit or interrogated. That said the empirical data has shed light on a number of cognitive phenomena, which were observed to affect the implementation process. Specifically the constructs supporting the assertion that implementation processes are guided by individual heuristics are: interpretive flexibility, mental models, cognitive prospection, creative confidence and perceived degree of novelty.

18.4.2.1 Interpretive flexibility

Disagreement over the nature of the 'problem' with the novel lime-pozzolan concrete floor is empirical evidence of interpretive flexibility. LA(A) implied that the aggregate had been the issue (lines 20-21), whilst ARCH(A) and ARCH(B) are seen to have still been expecting to utilise the site aggregate in a traditional polished concrete floor solution, as evidenced in the exchange in lines (97 to 104).

[LA(A)]: *'because you can have limecrete can't you with under floor heating but, it was the aggregate that was the issue.'* (lines 20-21).

[ARCH(B)]: *So for me though the aggregate is the main thing, the lime is brilliant that it is being used, but the great attraction of the product of the floor, was that you could stand and look at the floor and you'd be stood on the rock, the stone that would have been where you were stood, and I think that that would have been a really nice experience/* [ARCH(A)]: *But that still will happen* [ARCH(B)]: *Yeah I know* [ARCH(A)]: *But I think is where part of the problem came.*

Interpretive flexibility of an artefact is defined by Bijker (1995), as ‘differing ideas about what an object is or should be’, to which Schweber and Harty (2010) later added ‘could be’. This construct is illustrated in Figure 32.

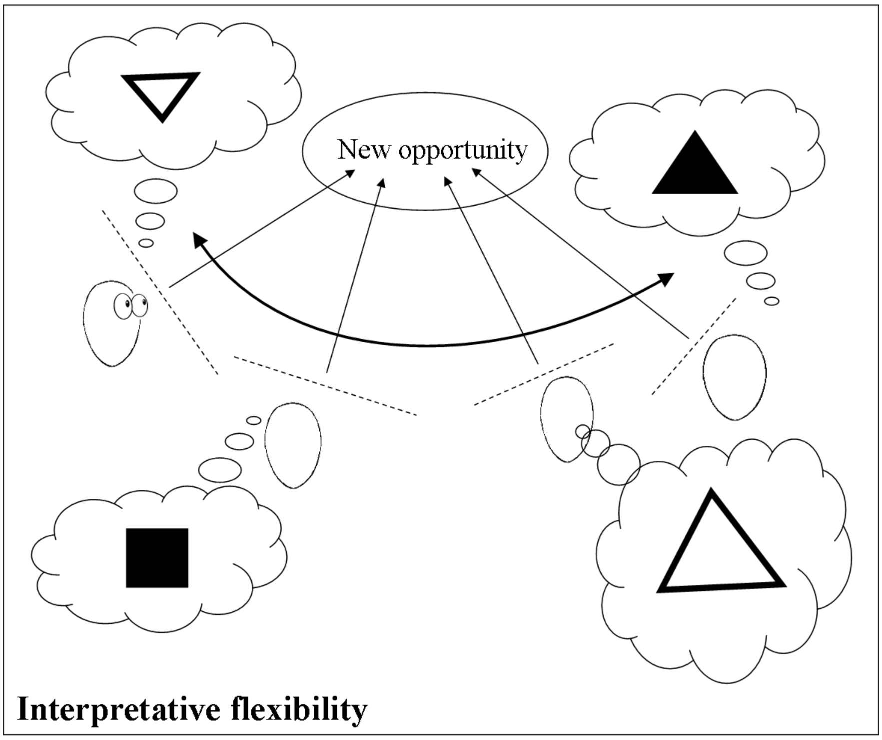

Figure 32: Interpretive flexibility

SLT(A) highlights another example of interpretive flexibility; how the same circumstances (in this case the discovery of archaeological remains) can be for some people a problem and for other people a hugely exciting moment, *‘You know when we said about the archaeology some people, and geo-phys people, getting genuinely really really excited whereas the jadedness of people involved in the project, who see these as problems and issues for other people are hugely exciting moments and how do you step back and make both of those things real for people....that is something that has touched me from the project’* (lines 87-91).

Interpretive flexibility is compounded in a construction project context, as project stakeholders are from different organisations, or widely different cultures, with differing values.

18.4.2.2 Mental models

Describing the polished lime-concrete samples SLT(B) is recorded to have said *'it was something akin to walking on marble floors in Italian buildings'* (line 42). This metaphor reveals SLT(B)'s mental model, in this case Venetian luxury as opposed to supermarket hardiness. Speaking about diamond ground concrete, the specialist polishing contractor is recorded to have commented, SS.CON(A): *'some people love it and a lot of people associate it with terrazzo (.) all that supermarket look'* (line 409).

(a) Villa Panza di Biumo, near Milan (Simonetti, 2011)

(b) Morrisons supermarkets, nationwide UK (Quiligotti Terrazzo, 2012)

Figure 33: Terrazzo floors

When a new idea or technology is presented to a group of people, they will all form their own individual 'mental models'. Often no more than word associations (e.g. terrazzo), these images are typically vague aggregations of pre-conceived ideas. Mental models, or schema, help us filter and integrate new information (Van de Ven, 1986). This construct is illustrated empirically in Figure 33 and generally in Figure 34.

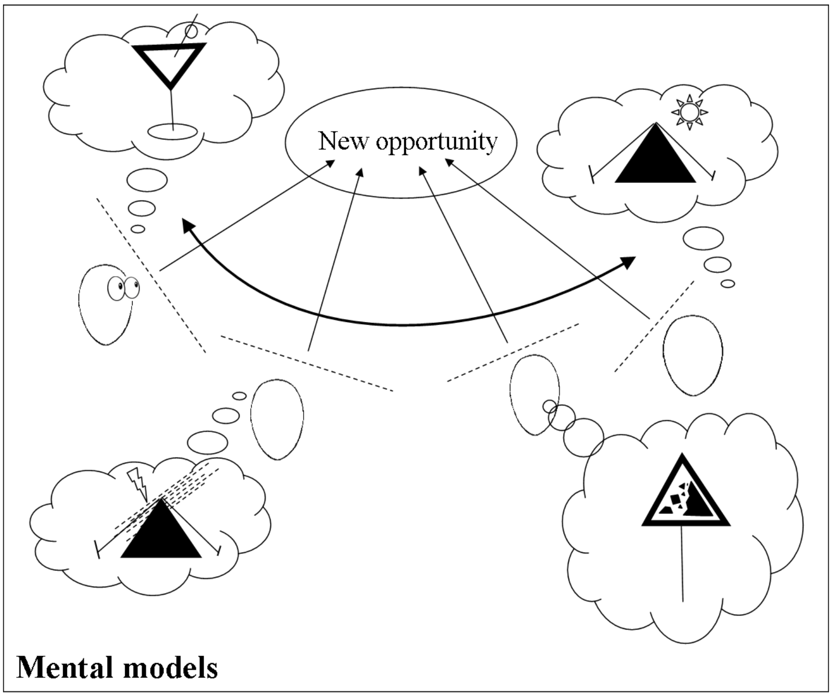

Figure 34: Mental models

Mental models not only affect how we process raw information and make sense of the world around us, but also how we act (Senge, 2006). For example it is recognised that humans are presupposed to 'cognitive bias', that is to seek out or adsorb information that reinforces their existing position or view, therefore, 'people tend to notice information that is related to information they already know' (Von Hippel, 1994). Sub-conscious mental processing can be a major challenge to pursuing innovative solutions, as Flood (1999) comments, 'obstruction to change sits mainly in the mind of the participants'.

Senge (2006) argues that the answer is to make these mental models explicit, preferably in a group context, forcing individuals to reflect on the accuracy and applicability of these otherwise subconscious pictures. Interestingly, if the design team were to have reflected on the applicability of the terrazzo floor finish, see both Figure 34 a) and b), they might have been expected to conclude that polished concrete is hardwearing and durable floor finish.

18.4.2.3 Cognitive prospection

It was observed that the physical samples encouraged and aided 'cognitive prospection' (Buckner and Carroll, 2007), that is the ability to envision the future, on the part of SLT(B). This demonstrated by the switch from use of the present to use of the future tense in lines 47-48.

[SLT(B)]: '*You know even the rammed earth just seeing the material from our ground, for it to be visible in anything, in any kind of building fabric is wildly beyond our dreams really, you know we'd never seen that before, and so for us <u>I was thinking wow that is great. Yeah – that could be fantastic,</u> and then we had – I sort of in my mind, although I struggle to see this building, and I sometimes wonder if I ever will, but I sort of in my mind I saw this floor from those samples and almost like you'd go and buy bathroom tiles for your bathroom and you might think oh yeah...<u>I could really see that in that room, I could just begin to see the whole room and you just walking in and seeing that floor and thinking just oh goodness you know how it would lift the whole building</u>.'*

This is also exemplified in lines 50-54 in which SLT(B) describes how the floor samples helped her to see the whole building in her mind. She later described such images as '*glimpses of the possibility of what could be'* (line 130).

Prospection is a cognitive mechanism used regularly and productively in decision-making processes, allowing a shift of perspective from the immediate environment to the imagined future environment (Buckner and Carroll, 2007). The availability of CLT, rammed earth and lime-concrete samples during the design process is thought to have helped individuals who were unfamiliar with these novel technologies, to create richer mental simulations of the final building.

18.4.2.4 Creative confidence and problem solving

The main contractor and the specialist sub-contractor showed evidence of what is argued to be 'creative confidence', in evaluating the buildability of the concrete floor. Creative confidence is defined as 'trust in one's own creative capability within an uncertain setting' (Plattner et al., 2012). There is purported to be a strong link between creative confidence and self-efficacy (Bandura, 1977), which is argued to 'supply the necessary conditions for taking action under risk' (Plattner et al., 2012). Four examples follow from the data:

[M.CON(A)]: *'Well we've never ever done this before, okay I'm sure some how we'll get it done….*

[M.CON(A)]: *Get it in the wall and then strike the shutting <u>and then hope everyone goes - wow, look at that</u> (laughing) (lines 510-511).*

[S.CON(A)]: '*So yeah, good and it works. I think the other massive challenge would be (.) and I know (.) scratch my head around it if it was to go into practise is how you would get the aggregate out the ground and get it clean enough to be able to use, to then batch it, to then pour it'* (lines 97-100).

[S.CON(A)]: *'Well if it was only 50m^2 (.) only 5m^3, <u>that would be achievable</u> still kind of archaic but (..)'* (lines 122-124).

Creative self-efficacy is defined by Tierney and Farmer (2002) as 'the belief that one has the ability to produce domain-specific, novel and useful outcomes'. Efficacy beliefs are described as the 'sustaining force that propels individuals to persevere in the face of the challenges native to creative work'. If creative self-efficacy is indeed conducive to creative endeavours, such as innovation, then it is understood that innovation can be fostered by the recognition and maturation of such self-efficacy.

18.4.2.5 Perceived degree of novelty

One observation from the case-study is that the degree of novelty of an innovative solution is very difficult to define and effectively communicate.

For LA(A) the degree of novelty of the polished lime-concrete floor appears to have been masked by a perceived association with 'limecrete' as a proprietary construction product. When asked whether or not it had been appreciated that the polished lime-concrete floor had been developed as a bespoke solution for this project, LA(A) answered, '*I think it probably ...it did but I think because limecrete flooring is becoming more and more common maybe the fact that it was slightly different just didn't really register...to ring alarm bells with me'* (lines 28-30). Retrospectively, the fact that the project team referred to this innovative material as 'limecrete' throughout the project may have been unhelpful in this respect. In LA(A)'s case communication of a higher degree of novelty might have been beneficial in prompting the innovation management processes deemed necessary, but equally had a high degree of novelty 'rung alarm bells' the material might have been prematurely eliminated. This implies a very subtle tipping point. The degree of novelty has to be sufficient to cross the threshold of action (Van de Ven, 1986) but not so high as to trigger a flight response.

Evaluating a novel technology draws on human prospective neural processes, through which the brain mediates past and future thinking. Novelty, by definition draws on the adaptive function of the brain, requiring individuals to extract and recombine information stored in their episodic memories to simulate a previously inexperienced future (Schacter et al., 2007).

As a result, the perceived degree of novelty of an innovation is dependent on each individual's prior experience and frame of reference. The specialist concrete contractor's frame of reference for evaluating the degree of novelty of the lime-pozzolan concrete was observed to be quite different from LA(A)'s. Rather than comparing this novel technology with 'limecrete', S.CON(A) compared the novel concrete technology with his experience of Portland-cement concrete. Asked how innovative he thought the lime-concrete was, he spoke about the general variability of concrete floors, S.CON(A): *'Every mix is different. Every mix is massively different, from one part of the country to another, from aggregate to and types, even cement types, alter it vastly, whether you are laying a 75mm slab or a 300mm slab, huge huge difference… every single place varies (.) so you have little tricks to deal with different places depending on where you are working'* (lines 205-208, 212). It is thought that this flexibility in the contractor's frame of reference, would have acted to damp out perceived dissimilarities with the novel technology and thus to facilitate its prospective adoption.

It is recognised that novelty is a defining attribute of any innovative solution (Rogers, 2003) but that the degree of novelty is not an objective reality but a subjective reality dictated by individual perception. The perceived degree of novelty stimulates an affective belief in each individual be it positive (interest) or negative (fear). Given that positive and negative affective beliefs will prompt vastly different behaviours, the degree of novelty has to be carefully qualified (Wells et al., 2010).

In a multi-disciplinary team not only is the degree of novelty of an innovation going to be highly asymmetrical but it is also going to affect peoples' evaluation of the viability and benefits of the new technology and thus also peoples' decisions. LA(C) for example, who had previously had a negative experience with 'limecrete', was unable to decouple this prior experience from the novel lime-pozzolan technology sharing the same name (documentary analysis).

18.4.2.6 Implications of implementation processes being guided by individual heuristics

The subliminal nature of heuristic decision making in engineering design, make these informal human processes nonetheless influential on the outcome. Compelling empirical evidence for decision making informed by individual heuristic judgements makes a strong case for managing the informal processes subtending innovation. Neumer (2012) writes 'The task of managing the informal is to enable and support decision making in the course of action'. One way in which decision-making can be supported in the context of innovation processes is by actively building shared meaning. Implementation does demand uniform meaning but meaning does need to be 'sufficiently compatible' (Warglien & Gärdenfors, 2011) to enable collective action.

For collective action in design teams the complexity introduced by the asymmetry of each contributor's prior experience can be beneficially reduced. Warglien & Gärdenfors (2011) purport that 'if concepts are convex, it will in general be possible for the integrators to agree on a joint meaning even if they start out from different representational spaces'. It is recognised that convergence on meaning, or 'meeting of minds' compatible' (Warglien & Gärdenfors, 2011) occurs naturally through conversation, but is asserted that in the context of design that the conversation might be beneficially facilitated to accelerate this natural social process. In the case of an innovative technology this might be done by using word association games to explore individual mental models or organising a visit to a manufacturer/research facility or similar project.

18.4.3 Theory 3: Implementation processes are guided by 'affective' decision-making

What emerged from the micro-sociological analysis of this case study was the recurring incidence of 'affect' in the design process. Affective, or emotional, reactions to stimuli are thought to proceed cognitive reactions and guide evaluative judgements and decision making, a phenomenon referred to as the 'affect heuristic' (Zajonc, 1980). The 'affect heuristic' suggests that 'people base their judgements of a technology not only on what they *think* about it but also on how they *feel* about it' (Slovic et al., 2004).

Like other heuristics, the affect heuristic is a mechanism for simplifying decision-making (Slovic et al., 2005). Human decision-making is thought to depend on two information-processing systems: experiential and rational. Innovation is thought to be inherently experiential for two reasons. Firstly, because it has been shown that novel stimuli, which can either be tangible or imagined, evoke stronger affective responses than familiar ones (Cox and Locander, 1987) and secondly because the high degree of uncertainty hinders rational thinking. Affective responses, which occur rapidly and automatically, are argued to be central to experiential thinking (Slovic et al., 2005), highlighting a relationship between this construct and the experiential nature of innovation as discussed in Theory 1.

The importance of 'affective' decision making in the case of implementation is its known influence on risk perception. It has been shown that although risk and benefit are positively correlated in the world ("speculate to accumulate") that in the mind perceived risk and perceived benefit are inversely correlated and guided by feelings or 'affective' responses. As a result of the 'affect heuristic' if an individual feels positively about a novel technology, they will tend to perceive that the risks of implementing it are low and the benefits are high. Conversely, if an individual feels negatively about a novel technology, the perceived risks will be high and the benefits low (Alhakami and Slovic, 1994; Finucane et al., 2000; Slovic and Peters, 2006).

In this case visual attractiveness, representation (discussed in relation to Theory 6), sensory evaluation and innovation stories are all purported to have heightened the 'affective' experience of the design team.

18.4.3.1 Visual attractiveness

Empirical evidence pointed to the perceived desirability of the polished limecrete floor finish. It is discernable from the interviews that SLT(A) had thought that the limecrete floor was beautiful, '*but what was so nice about the samples was that they were beautiful, so just for the simplicity of elements from the ground'* (lines 14-15). LA(A) similarly thought that the floor would have looked beautiful, LA(A): '*I thought it would all go swimmingly, that we would have it in and it would all look beautiful....laughing'* (lines 13-14).

ARCH(A)'s comment, in lines (97-101), highlights that it was not the novel lime-pozzolan binder that made the polished samples attractive, but the use of site-won limestone as aggregate, '*the lime is brilliant that it is being used, but the great attraction of the product of the floor, was that you could stand and look at the floor and you'd be stood on the rock, the stone that would have been where you were stood, and I think that that would have been a really nice experience.'*

With the samples on the table during the follow up conversation SLT(A,2) reiterates, *'I've got to say you can't help but look at that and be all (prrrrrr) // Yeah. Yeah it is really nice'.* Implying that it had been pointed out to her that the novel lime-binder could not be seen, SLT(A) then commented, *'I k*now *you can't necessarily see the lime - but you know it is just like (prrrring)'* (lines 201-203), going on to say, SLT(A,2): '*They are truly truly beautiful and I just think it's just stunning' (line 205).*

Perceived visual attractiveness is reported to be a 'positive affective belief' (Van der Heijden, 2003) and is thus purported to have impacted the implementation process by '*downplaying the risks associated with adopting a product or technology'* (Alhakami and Slovic, 1994). On the basis of the 'affect heuristic', those members of the design team who perceived the attractiveness of the material samples may have been desensitised to the risks associated with implementing it. By the same token the ultimate decision maker, whom in this case had not seen the samples, could not have been influenced by this visually informed heuristic.

The following two constructs are observed to be closely tied to visual perception. The first building on SLT(A)'s comment *'I know you can't necessarily see the lime'* (see section 6.3.3.2) and the second on ARCH(A)'s comment '*I think that probably one of the issues was just that the samples looked brilliant and it all, when you knew the story'* (lines 78-79) (see section 6.3.3.3). This comment implies that the appeal of an innovative solution is partly embodied in its story. Evoking affective feelings narratives are argued to be another way in which humans encode reality (Slovic and Peters, 2006).

18.4.3.2 Observability of the innovation

Emerging from this case study is the obvious importance of the visibility of the innovation in the finished building. In this case the novel lime-pozzolan binder was imperceptible in the finished floor. This is discussed by the architects in the excerpt in lines (83-93).

[ARCH(A)]: (.) *it was fantastic. But I think that the people like the school got confused about the (.) when they heard they couldn't have limecrete they thought it was going to look like an entirely different product. As opposed to actually it's still looking quite similar and not having lime as the kind of agent* [ARCH(B)]: *Yeah* [ARCH(A)]: *but actually/so I think that when they still heard that they could have lumps of lime in it, bits of the school that they felt reassured. And I kept getting con(.) I knew it was limecrete not concrete but I kept coming back and looking at it and treating it like a polished concrete sample. // [ARCH(B)]: Using (.) // // [ARCH(A)]: Not thinking about what kind of cement was used, when in fact it was a completely different product. So* /

Two factors come forward from this excerpt. Firstly, this implies that it was the visible use of site-won limestone as aggregate that was important to the school, as opposed to the innovative binder, which ARCH (A) describes as 'the real innovation', ARCH(A): '*Is that //that the real innovation was hidden//.* [ARCH(B)]: *//aesthetically, experientially in may not actually// Yeah.'* Secondly, that ARCH(A) struggled to differentiate this novel technology from polished concrete, ARCH(A): '*Try and not lose the good work and research, even if it were just concrete benches or something. Sorry - see there I go again. Limecrete benches*' (lines 218-220).

ARCH(A) tentatively made the point that if the innovative floor had looked distinctive, there would have been a better case for specifying this innovative technology rather than a polished concrete alternative, ARCH(A): '*So if it had looked* <u>*so*</u> *completely different, not looked like a standard polished concrete floor, there may have been more weight to the argument. I don't know, I'm not sure'* (lines 111-113).

This theme also emerged from the analysis of DTM02 and DTM03, which supports the idea that the innovation has to be visible in the finished building, to make the investment in its implementation worthwhile. This implies that the value of an innovative technology is not wholly realised by its fruition, nor by its operational benefits (assuming these would not be compromised by its being hidden). Rather, the value of applied-innovation is at least in part secured the long-term readability of the artefact.

SLT(B): *'this should be something for posterity that we can really say that we are proud of that we really pushed the boundaries, that we really innovated with and people will come and say wow – you did that, that was really cutting edge when you did that, that was amazing.' (lines 91-98).*

On-going value to the adopter may be egocentric (the innovation being a symbol of modernist progress) or altruistic (the readability of the innovation encouraging diffusion), or a combination of the two. Certainly, observability of an innovation is one of the five characteristics of innovative technologies that Rogers (2003) argues to be beneficial for the diffusion of innovation.

Desired readability is also a statement of the adopter's confidence in both the benefit and effectiveness of the applied-innovation. Clearly observability would be, or become, a negative attribute of applied-innovation if the artefact was perceived to be disliked or unsuccessful. As Klein and Sorra (1996) point out *'effective implementation does not guarantee that the innovation will, in fact, prove beneficial'*

18.4.3.3 Observability of the innovation story

In an extension of the previous construct, there is evidence to suggest that when the innovation itself is undetectable, that the innovation story should be appreciable, ARCH(A): '*I think that probably one of the issues was just that the samples looked brilliant and it all, when you knew the story*' (lines 78-79). ARCH(A) is thought to have been referring to the project specific story; namely the discovery and use of site-won limestone as aggregate, two phases of testing carried out at the University of Bath and development of a bespoke solution in collaboration with the design team and a specialist contractor. He could also have been referring to the broader technological story; namely the modern application of an ancient building technology. Perhaps he was even making reference to the overlap between these two stories that was unique to both this Roman city and to this school, which commemorated the individual quarrying the limestone (utilised as aggregate) in this precise locality in the 17th century.

Ultimately the challenge was the same in whichever case; if these stories were inherent to the value of the innovative floor, then how could they be captured and communicated to the future building users? Expressly referring to the project story ARCH(B) commented, '*It would have been great as well to have had that to talk about in the future'* (line 125). For an architectural practice priding itself on the delivery of 'pure and conceptually strong buildings' this innovation story is thought to have been part of the 'strength' of this building design, ARCH(A): '*I think in terms of the story of the building it was very important'.*

The importance of stories in design is recognised (Chapman and Gant, 2007). There are thought to be three primary dramatic plot lines structures in storytelling: overcoming the challenge ("David and Goliath stories"), making a connection ("Good Samaritan stories") and inspiring creativity stories, such as this one (Beckman and Barry, 2009). During the design process storyboards were utilised to tell the research story to the design team (see Appendices E & F). Given that narratives are recognised to evoke affective feelings (Slovic and Peters, 2006), it is argued that this would have acted to heighten the affective experience of the design team, the implications of which is discussed further in section 6.3.3.6.

18.4.3.4 Sensory evaluation

The following excerpts provide empirical evidence that touch or 'haptic perception' may have been significant in the evaluation of the sustainable and innovation materials in this case.

[SLT(B)]: *'well first of all, I thought it was great when you brought the materials along to the meeting when the kids were there, when they actually looked at them and physically got in touch with them, I think that that was a really important meeting that they actually began to realise that this was different… that was when I saw the excitement that the young people would get out of engaging with these different materials and understanding that you could physically touch and handle and enjoy contact building materials was quite a new thing really'* (lines 32-39).

[SLT(B)]: *'for me it is about this contact, this physical contact with the environment, through the building – that you go in and you see it and you feel it and...I don't know you touch, you can smell it even' (lines 132-134).*

In the retail industry the ability of a customer to touch product offerings has been found to influence buying behaviour. 'Tactile input' has been observed to be powerful in the evaluation of products and thus also on purchase decisions (Grohmann et al., 2007). There is increased interest in understanding the interrelationship between sensory evaluation and behavioural outcomes. Touch not only facilitates a sensory evaluation of quality but is recognised to increase perceived ownership, both of which contribute to the decision making process (Balaji et al., 2011).

Analysis of the design team meeting using De Bono (1999) 'Six thinking Hats', demonstrated that handling the samples tended to evoke a 'red hat' response. This evidences a relationship between tactile input and an affective mode of thinking.

Given the reported relationship between the 'affect heuristic' and human risk perception, empirical evidence identified as pertaining to perceived risk is unpacked in section 6.3.3.5, before the implications of 'affective' thinking in implementation processes is discussed more generally.

18.4.3.5 Perceived risk

Like novelty, risk is recognised to be an inherent attribute of innovation and a largely subjective phenomenon. The following excerpts provide evidence of three individual members of the design team describing of the risk involved in implementing the novel lime-pozzolan concrete technology for the first time. The use of qualitative language in describing the degree of risk is evidence of the subjective nature of risk perception.

[ARCH(A)]: '*I think that by limiting it to the ground floor and the areas that we did, I thought we also that, it was <u>taking out lots of the risk</u> in terms of whether it did take longer to cure or (.) contractors kind of working around it, so I thought (.)* (lines 44-48).

[SLT(A)] *'how hard it is to make spaces for <u>what aren't huge risks</u>'* (line 33).

[ARCH(B)]: *I didn't see, I didn't/I mean (.) it is innovative but <u>I didn't think it would be so innovative that it would be</u> <u>too risky</u>. I don't know the technical side, so much but it seemed that/I didn't understand why you couldn't do - what/you know direct replacement'* (lines 30-32).

Field notes made following the meeting about the novel lime-pozzolan concrete floor, note that LA(C) (the ultimate decision maker), commented *'If there is any risk I am not taking it'*. It is not possible to pin-point the degree of risk in this case, only to interpret from LA(C)'s actions, specifically his request that the specification be withdrawn, that he perceived the risk of implementing the novel technology to be *too* great.

A number of behavioural economic theories have been developed to model human decision-making processes (Kahneman, 2003). Though decision-making models vary they generally concur that people only assimilate risk (potential loss) in the expectation of some reward (potential gain). LA(C)'s unwillingness to take on any risk in this case, may act to highlight the lack of perceived benefits. Specifically LA(C) is recorded to have commented *'I don't see the educational benefit'* (documentary analysis, 15.03.12). The lack of benefits to the local authority was highly problematic in this case (Ivory, 2005). Having said that, LA(C) did clearly appreciate some educational benefit as he is recorded to have commented *'we can do a demonstration area outside, as an experiment and an educational resource. As long as it is outside the building and off the critical path'.* LA(C)'s specific concerns about the implication of the lime-pozzolan concrete on the construction programme and the operational performance of the finished floor were reiterated in the conversation recorded in the documentary analysis (15.03.12):

[LA(C)]: *'The project has a suicidal programme anyway; this will take weeks to go off'.*

[LA(C)]:*'I want to go and see it in another building. In another school so we can see its wear and slip resistance.'*

[LA(C)]:'(Project x) was about pushing the boundaries and it all went wrong.'

In the discussion about the experiential nature of innovation processes, it has been observed that positive affective responses, such as excitement and interest, are motivational to the process. By the same token, negative affective responses, such as fear or nervousness, hinder innovation. In this case-study 'nervousness' was expressed by a number of members of the design team. Interestingly, the following extracts reveal that the nervousness experienced by different members of the project team was not caused by the same prospective events.

ARCH(A): *'ironically I felt more nervous about things like the rammed earth than the limecrete'* (lines 14-15).

ARCH(A): *'So I thought the limecrete, I thought we might have been able to push that one through, but yes, so I think I felt confident until I had a meeting with* (the local authority), *where the more senior person came in and was incredibly damning about it, and kind of nervous'* (lines 19-22).

ARCH(A): *'But not// just nervous, I mean he was (.) he just said if there is a risk we're not taking it'* (lines 26-27).

The main contractor also spoke about his fears over unfamiliar aspects of the design. The main-contractor expressed nervousness about the dry-shake floor being laid (this was the proprietary concrete floor system that superseded the lime-pozzolan option). M.CON(A): **'***And I am quite looking forward to sorting this floor out. But nervous of the floor'* (lines 525-526). Although the contractor's relative wariness over the potential lime-pozzolan concrete screed and the dry-shake screed cannot be deduced, it is interesting that the innovative lime-pozzolan concrete was evidently not replaced by a mainstream solution that the contractor was familiar with.

The following excerpt suggests that even the specialist sub-contractors that the main-contractor approached to lay the dry-shake floor screed, considered even this an 'experimental' application of this technology, M.CON(A): '*We had gone to a couple of our tried and trusted, known them for twenty year, floor type people, screeders and things like that. And they have written back and gone (...) they don't want to experiment with that as a job, here. They said if it was like some other sort of location, and (.) but you know because of the nature of the job, and it is high profile, they don't want to use us as a guinea pig with that material, which is the honesty I was looking for. Because if it goes wrong you've got a complete mess on your hands'* (lines 210-217).

The other interesting point emerging from this conversation is that the sub-contractors willingness to experiment is clearly influenced by the profile of the project. In this case this project was deemed too 'high profile' for use as a 'guinea pig'.

Regardless of the main contractors 'wariness' of both the dry-shake floor and the rammed earth wall, these 'one-offs' both went ahead and were implemented in this project. '*Yeah, you are a bit wary of it. Okay. You know I have been in this industry since I was eighteen, so that the things that (indicating the dry-shake floor system paperwork on the table) tend to bite you in the backside, generally as a contractor are the one offs, like that could bite us in the backside'* (lines 235-238). Talking about the rammed earth wall the M.CON(A) was observed to comment, '(The rammed earth wall) *really is as far as I am concerned as a contractor it is still one of those' (gesturing crossing his fingers)* (lines 411-412).

In this case the main-contractor evidently appreciated that there were risks associated with the one-off aspects of the scheme, however the ‘wariness’ he expressed of the rammed earth wall and the dry-shake floor screed, was not sufficient to prevent these being implemented. Action can be taken under risk, in this case the action the main contractor took was to find and employ an experienced sub-contractor to whom this risk was assigned.

18.4.3.6 Implications of the ‘affective’ decision-making on the management of implementation process

It is argued that ‘affective’ decision making was highly influential throughout the innovation story in this case study. Firstly, it is asserted that the initial consultant interview, at which the possibility of utilising innovative and sustainable materials was first introduced, prompted a positive affective response in the school, which resulted in applied-innovation becoming part of the design philosophy of the project. Secondly, it is supposed that the decision to omit the novel lime-pozzolan concrete from the design was probably also a decision guided by the ‘affect heuristic’. This inference is supported by the Slovic et al’s (2004) theory that the governance of the ‘affect heuristic’ is enhanced by time-constraints, which hinder analytical reasoning in decision-making. Unlike the rest of the design team, the decision maker was not actively involved in the design process and thus not influenced by any of the shared experiences that had acted to build a shared positive affective belief in the novel technology. Rather, prior negative experiences of both ‘limecrete’ and ‘applied-innovation’ informed a negative affective belief, which would have over-weighed the perceived risks and downplayed the perceived benefits in this instance.

Retrospectively, it is argued that the material samples, the storyboards, the use of site-won limestone and the fact that members of the design team were alumni of the school, were all features of the case study project that acted to stimulate and heighten positive affective beliefs, which were reinforced by the social contagion within the design team (see section 6.3.4.1). The ‘affect heuristic’ is thus believed to explanatory in describing why the technical risks associated with implementing novel aspects of the design were downplayed by the design team and why the concurrent design and research processes generally proceeded on ‘risk as feelings’ as opposed to ‘risk as analysis’ (Slovic et al., 2004).

Writing about how individuals and design teams can improve their ‘innovation competence’ Bauer (2012) promotes the use of games to facilitate a playful attitude to innovation. However he recognises that ‘when the “game gets serious”, the game mode has to be abandoned and the real mode is addressed on a meta level'. Similarly, affective decision-making is thought to be beneficial in the early stages of innovation processes, but has to abandoned in favour of formal decision-making strategies when the process 'gets serious'.

Affective decision making in implementation processes is thought to be highly consistent with Bauer's (2012) playful approach to 'Innovation Work', for affective experiences have been observed to contribute to the same immersion and 'suspense of disbelief' that is promoted by play. Like play, experiences seen to stimulate or heighten affective responses (sensory evaluation, stories & representation) are purported to be a valuable strategies for encouraging design teams to adopt an open attitude and accommodate a high degree of uncertainty at the outset of applied-innovation process.

However, the outcome of this case study project is thought to have highlighted the importance of the timely transition from 'risk as feelings' to 'risk as analysis' (Slovic et al., 2004). In this case the transition from 'the game' to 'reality' is purported to have been made too late in the process, with specific risks not being identified, or at least not voiced, until it was too late in the project programme to satisfactorily address them. Formal risk management procedures are beneficial in encouraging and facilitating a reasoned and analytical evaluation of risks and are argued to be essential for mitigating and assigning risks. Slovic et al. (2004) argue 'when risk as feeling tends to overweigh frightening consequences, we need to invoke risk as analysis to give us perspective on the likelihood of such consequences'. As a result, a strategic approach to managing the risks associated with innovation processes is purported to combine both 'affective' experiences, which promote risk as feelings, and formal risk management strategies.

The fourth theory underlines the social dimension of innovation as a human process.

18.4.4 Theory 4: Implementation is a social process

Two themes emerging from analysis of the interview data emphasised the influence of social network effects in design. These observed phenomena were recognised as being constructs described in the extant literature as social contagion (Burt, 1987) and interessement (Akrich et al., 2002) respectively.

18.4.4.1 Social contagion

Scherer and Cho (2003) have concluded that group dynamics have a significant effect on the perception of risk. *'Adopting an innovation entails risk, an uncertain balance of costs and* *benefits, and people manage that uncertainty by drawing on others to define a socially acceptable interpretation of* risk' (Burt, 1987). This social phenomenon, known as 'social contagion', attests that an individual's perception of the risk of innovation, is evaluated in the light of the evaluation of others in his/her proximate social network; be that friends, family, colleagues or a wider community of adopters (Burt, 1987). Social contagion is evidenced in a number of the interviews, most clearly in LA(A)'s utterance '*…I think as well because you were doing so much work on it and always coming with....so much effort had gone into it...that you do have a level of trust don't you...and I don't know, it seemed like a really sound idea to me'* (lines 41-43).

It is purported that *'confronted with the need to make a decision in an ambiguous situation - a situation that does not speak for itself - people turn to each other for clues'* (Burt, 1987). This is seen to be the case for the main-contractor, who being new to the design and without a design team to draw on, was seen to go out in search of *'tried and trusted, known them for twenty year, floor type people'*, whose perception of the risks he then used to inform his own interpretation, [M.CON(A)]: *'they don't want to use us as a guinea pig with that material, which is the honesty I was looking for. Because if it goes wrong you've got a complete mess on your hands'* (lines 210-217).

The architects are seen to have drawn their perception of the risks, not explicitly from the design team, but from the lime-pozzolan samples panels themselves (lines 36-40).

[ARCH(B)]: *And the samples looked brilliant so//*[ARCH(A)]: *Yeah. I think//*
[ARCH(B)]: *That was most convincing//* [ARCH(A)]: *Yeah* [ARCH(B)]: *When you*
saw the samples (.) [ARCH(A)]:: Yeah [ARCH(B)]: *You thought actually this looks*
like a proper product, proper construction system.

When the design team was considering the use of an unfamiliar technology, the uncertainty was distributed across the group, which limited individual evaluation of the perceived risks. Social contagion is beneficial to a point, as it allows a higher overall level of uncertainty to be tolerated, or 'held,' for longer. The ability to hold the uncertainty buys valuable time for seeking out the information that will be effective in reducing it.

The stronger the relationships between members of the design team, the greater the level of respect for other's evaluation of the innovation and the easier it is for all members to tolerate the uncertainty. Speaking about the relationships within the design team SLT(B) is recorded to have said, '*but you see – whoever said that*) *wasn't witnessing the working relationship* *that we had built up…All the times that you spent here and we've sat in meetings and discussed and discussed and discussed'* (lines 143 & 147). Frequent and empathetic communication is key to building strong relationships characterising a cohesive network (Burt, 1987).

In this case study project the ultimate decision maker LA(C) was not an active member of the design-team and his evaluation of the risks associated with adoption of the novel technology was not influenced by that of others in this cohesive network. The fact that there was no time in the programme for LA(C) to 'hold' the risk associated with the novel technology is thought to be evidence that he was brought in to the design process at too late a stage. Earlier involvement might have bought time for him to be reassured by information, physical evidence or the interpretation of others in his own network.

Interpretive flexibility and social contagion are both phenomena that should be taken into account during design processes, as they're influential in shaping individual perceptions of artefacts, and importantly the risks and benefits associated with adopting them. In this case study social contagion is thought to have supressed the need for an explicit risk management procedure.

Writing about what they describe as 'the Art of Interessement' Akrich et al. (2002) argue, 'the outcome of a project depends on the alliances which it allows for and the interests which it mobilizes'. Interessement is a social process of pro-actively creating alliances to support innovation. In the construction industry, competitive tendering hinders innovation by precluding interessement during the initial design development process.

18.4.4.2 Interessement

Many authors on innovation subscribe to a network-perspective (Callon, 1986, Akrich et al., 2002b, Latour, 2005, Christiansen and Varnes, 2007); like Isaken (2011) acknowledging that, 'people are key in implementing all change efforts'. The concept of 'interessement' goes one stage further and argues that networks can be proactively created and manipulated to 'aggregate' or 'mobilise' interests (Akrich et al., 2002a), to further projects and achieve desired outcomes. Describing the model of interessement, Akrich et al. (2002a) asserts that, *'the fate of the innovation depends on the active participation of all those who have decided to develop it.'* He goes on to say the *'art of interessement' is knowing on who and on what you can rely to bring a project to a good end'* and *'endeavouring, through negotiations and* *socio-technical compromises, to interest more and more actors'* (Akrich et al., 2002a). Harty (2005) refers to this process as *'heterogeneous engineering'.*

Competitive tendering makes it difficult for project teams to elicit the input of contractors, or other specialists, during the design development stage. This was certainly the case in this project, ARCH(A): *'I suppose interacting with manufacturers would have helped more. If there had been/ If there had been a way of appointing// someone to do that before tender'* (line 199).

Presented with an innovative building at Stage D, interessement, or '*bringing on people who do know more about it than you'* (line 242) was observed to be the primary activity of the main contractor at T1. [M.CON(A)]: *'You know the industry, you know construction, you have done thousands of projects over many many years, but its genuinely those sorts of things where you go, What is all that about?, or it's got slightly unknown factors, you do your research, you know you bring on people who do know more about it than you'* (line 240-242).

Having identified where individuals with specific knowledge or skills needed to be found, the next stage was to find, contact and engage suitable parties or individuals. It is observed that M.CON(A) had difficulty identifying a specialist sub-contractor to approach about the novel lime-pozzolan floor, [M.CON(A)]: *I was running into a little bit of a brick wall with the floor, I didn't have a contractor to go to, I couldn't really Google it and things like that, you are kind of not finding somebody jumping out* (lines 243-245). Increasingly search engines are the first port of call for the unfamiliar, which is why Search Engine Optimisation (SEO) is increasingly germane.

Finding no specific party 'jumping out' M.CON(A) was evidently forced to break the construction of the floor down into sub-tasks, specifically seeking out parties that might be interested in grading the site-won limestone. Identifying companies with the capability to undertake this activity is seen to be only part of the process of interessement (138-150),

[*M.CON(A)]: One of the big items was the limecrete floor. // Okay // Which we obviously did some research on. We even ran into things like going to companies like Cemex, who are obviously worldwide (..) We said to Cemex (.) we know their rep and everything else ' Can we run excavated material into Cemex's plant, and can we actually get you to grade it down to the kind of grading criteria that was in the Ramboll spec, to then obviously mix on site?' And they actually refused and other*

Hansons refused to do that. They do not take other peoples material in, grade it and put it back on a lorry. So they were of no use with that at all. So we approached more local companies like M.J. Church, you probably know, and they were quite happy to receive our lorries, run in through their sieves and they would use a riddling bucket, here first, that was our plan (.) use a riddling bucket, get everything down, perhaps instead of big lumps, get it down to perhaps 100mm down, take it to somewhere like Mike Church, he puts it through his sieve, because he does recycled aggregates up there anyway, you probably know //Oh, okay // and then get it back to the site here to put into the slab.

Some parties are observed to be resisters and some assistors in this case. A notable challenge of interessement at T1 was that all that the main contractor was trying to do was to accurately price each element of the design. For those suppliers and contractors approached by M.CON(A) at this stage there is no guarantee of ultimately being involved in the project, even if M.CON(A) is himself successful at winning the contract. Innovation requires sub-consultants to price unfamiliar tasks, a potentially time consuming activity in its own right, that must be undertaken at their own risk. Each sub-consultant has to consider not only their inherent capability but the likelihood and benefits of ultimately winning the contract. Evidence of this interessement process is particularly rich in the case of the rammed earth sub-contractor RE.CON(A),

[M.CON(A)]: *'So I had a couple of long chats with him* (RE.CON(A))*, the first chat I had with him is a bit of a disaster because I said I have got this job and he went 'oh a school sounds good, okay tell me more - what is the length of the wall?' 6 metres. 'Sorry". 6 metres. 'Six metres! You have got to be kidding.' So he thought it was an absolutely ridiculously small project, ridiculously small, in fact he still does (.) So I was like well are you interested or not? 'Well not really'.*

Given the lack of competition in the UK market for the construction of rammed earth, lack of interest on the part of RE.CON(A) of constructing such a 'ridiculously small' wall, threatened the implementation of this aspect of the design. In this case RE.CON(A) was observed, over a period of a week, to have found an interest in this project and have phoned M.CON(A) back.

[M.CON(A)]: *Anyway about a week later, when I was thinking oh no how am I going to price this…he rung me back, and he said 'Oh come on then, let's have another talk, send me some* *drawings over.' he said ' It sounds like a right pissy little project, but oh okay we are not doing many in Britain, so this might be one for the folder'. I said well come on now you are talking* (lines 372, 376-380).

Highlighting the active nature of network building, Christiansen and Varnes (2007) state that, *'Interessement is an active process of trying to establish strong relationships and networks'.* One phenomenon that was evidenced in this interview is that the main contractor's interessement process was affected by the local authority's and the architect's own networks (see the excerpt in 297-307).

297 [M.CON(A)]: *'take* (CLT.CON(A)) *as example, because that is who we've employed*
298 *ultimately, the costings were very very close, but we went with* (CLT.CON(A))
299 *because a) we know they have done a job for* (the local authority) *and b) Of course*
300 *we'd appointed* (Architecture practice A) *as our architects, so they work for us now,*
301 *and of course their offices are like half a mile from* (CLT.CON(A)), *so when we had*
302 *that very initial meeting with* (Architecture practice A), *to say right okay welcome on*
303 *board chaps, what are we going to do about this job then, let's get a plan up*
304 *together, one of the first things on the agenda was key sub-contractors so of course I*
305 *said, well CLT, and they said is there anyway you can please use* (CLT.CON(A))*?*
306 *So we did a deal with* (CLT.CON(A)), *because on paper they weren't quite the*
307 *cheapest (.) Did a deal with* (CLT.CON(A)) *and appointed them.*

Interessement purported to be a social-process that could be leveraged to support innovation in construction. In this case study interessement was almost entirely limited to the main contractor during the tender period. A notable exception was the specialist polishing sub-contractor, who furthered the applied-innovation process by polishing the lime-pozzolan sample panels during Stage D.

18.4.4.3 Implications of implementation being a social process

Fragmentation and adversarial relationships in the construction industry have long been recognised as a barrier to innovation (Saad, Jones & James, 2002). Calls for procurement reform and increased partnering (Latham, 1994 & Egan, 1998) have repeatedly stressed the benefits of inter-organisational relationships based on openness, cooperation and long-term interests rather than short-term, arms-length relationships bases on rigid-contracts and competition, which so easily end in litigation (Cox and Thompson, 1997 & Dubois and Gadde, 2000).

Yet, common place forms of procurement, such as Design and Build (D&B) in this case study, do not allow for design as a social process. Specifically, the transfer of the design from the client led design-team to the main contractor interrupts the social process, almost instantly, changing the relationships between the client, the design team and the design. When the Design and Build contractor takes on the design he inherits only the design as it is captured on paper, in drawings, specifications and employers requirements. Emergent properties of the design process – ‘psychological investment’ (Bird, 1988), commitment (Slaughter, 2000) and collective intentionality (Schweikard and Schmid, 2013) are easily lost at this juncture. Further still, social capital accrued during the design process can by undermined by the competitive tendering process, in which members of the design team can end up pitted against one another on different contractor-led teams, as was the case in this project. The architect was teamed with the winning contractor and the structural engineer (Ramboll UK) with a contractor that withdrew during the tender process, for reasons that weren’t even known.

Recognition that implementation is a social process, puts strategic importance on the relationships between the project stakeholders, the attitude towards collaboration and the choice of procurement route.

The first four theories pertained directly to the human actors in the applied-innovation system. The following five theories, also identified from close scrutiny of the empirical data, pertain to the implementation process itself. The emergence of anthropocentric phenomena in this section, acts to reinforce the final theory that implementation processes are mutually constituted (see Theory 12).

Although generalizable theories are recognised to be valuable in looking across case-studies, the project-specific nature of applied innovation makes it inherently contextual. Although this thesis argues that design process in construction can be managed to support innovation, it is appreciated from this case study that exogenous factors are always going to have a bearing on the outcome. Theory 5 acknowledges that innovation processes are contextually embedded and calls for express consideration of the contextual factors that influence implementation at a project-level.

18.4.5 Theory 5: Implementation processes are contextually embedded

18.4.5.1 School specific context

One recurring theme was school-specific constraints on innovation. LA(A)'s comment, '*It's disappointing but [erm], I think it was right to point out the risks … I think the compromise had to be made really, I think we can't really innovate with public funds on a school* (lines 11-12 & 13-14) appears to emphasise that is the use of public money for innovation that is improper. Whereas SLT(B) implies that is the 'sanctified' nature of schools that seemingly renders innovation improper in this specific context (lines 128-134),

128 *'I think the unfortunate thing was(..) people kind of think about a school as*
129 *something kind of sanctified, that you just can't risk anything, because it is a school,*
130 *and you think well ...I just go in that vicious circle of thinking well – how do you*
131 *innovate if, and you should be innovating in school buildings, if innovation is never*
132 *for education settings, it's never for this – then it won't be innovation, by the time is*
133 *comes down to schools, it will be twenty years old and tested and tried and*
134 *something better might have come along.*

These two perspectives on the situation are quite different, but resulted in the same final conclusion; that an innovative solution was improper in this particular project. Having been able to recognise that an innovative solution was going to be deemed improper in this project, regardless of the school's expressed desire, could have saved considerable effort on the part of the design team. (Ivory, 2005) similarly suggests 'It would be useful, for example, to be able to identify what type of clients, in what sort of circumstances, tend to support of supress innovation'. Certainly, this experience raises questions about the design team's awareness of the local authority's (the client) requirements.

Whether or not the implementation of innovative solutions is a 'responsible and effective' use of public money (HM Treasury, 2013) is in itself an interesting debate. If it is only through the application of innovation that benefits are ultimately realised, then it might be argued that applied innovation is essential for realising value from public investment in research. The Council for Science and Technology certainly argue that 'commitment to enhance expenditure on the research base and on support for its translation into economic benefit would be both an investment in the UK's short term growth and our longer term prosperity and place in the world' (Council for Science and Technology, 2013). The translation of research investment into economic benefit is a strong argument for encouraging innovation in publically procured construction projects. The second project-specific construct identified from the empirical data related to the performance of the innovative technology in use.

18.4.5.2 Durability performance

Concern about the durability of this novel material technology was almost certainly a determining factor in the local authority decision to omit the bespoke lime-pozzolan concrete floor. Commenting on the durability of the lime-pozzolan concrete, the main-contractor who went on to complete the building is recorded as having asked, [M.CON(A)]: *'is it actually okay to take all the traffic for the next 50 years on the finished surface?' I mean do people know that that is actually going to work? And stay and not need remedial work (.)'*

Defects, which include material deficiencies, are reported to be the major cause of disputes and litigation in construction (Glover, 2006). In a Design and Build Contract the main contractor is legally responsible for ensuring that the finished building is 'fit for its intended purpose'. Unlike an architect's or a consultant's responsibility to 'exercise due care, skill and diligence' the contractors legal obligation is absolute. Typically, a contractor's responsibility for defects becomes 'statute-barred' after six years after completion of the project, although the period of the contractors liability extends to twelve years if the contract was under seal (Glover, 2006). The precise nature of the contract is not known in this case.

Either way, this meant that if the performance of the novel polished lime-pozzolan concrete floor proved to be a problem within six, or twelve, years of it being handed over to the client, that the contractor would be liable for damages, which is typically 'the cost of reinstatement taken at the time that the defect was discovered' (Glover, 2006). In the case of this project, the larger contractors were not happy to back the novel system, as the perceived risk of technical defects leading to damage claims was too high.

[M.CON(A)]: *'I just found out on pro-contract, was a lot of the large contractors the nationals weren't okay about the guarantee element of the limecrete floor, in terms of durability. Because obviously with NEC 3 I think there is 12 years liability for the* *floor, well for the job (.) so people raised it on there and said they weren't happy to back that system'*

The smaller main contractor, who was ultimately appointed, recognised the larger contractors' concern about the durability performance of the floor, but did not 'latch on to the liability angle' in the same way, for they went ahead and tried to price this novel aspect of the design, before later learning the client had withdrawn it.

[M.CON(A)]: *'I can see how some of those bigger contractors would have latched onto the liability angle on that. The trouble is you know, if you have got something that isn't fully tested, generally when something starts to breakdown in any way, however small, it is almost irreversible then, you never know how far it is going to break down until it happens. Because with those stones if something starts just moving, not moving, but wearing down in a certain way, what does it then next do?'*

This is evidence of a variable risk tolerance in contractors. The large contractors in this case demonstrated a low risk tolerance, allowing little time for evaluation of the novel technology. Whereas, the smaller contractor's response to the innovation was to try and work out how the site aggregate might be graded, in order to cost this aspect of the tender for the client, the larger contractors quickly highlighted the innovation to the client as a high risk item.

The third context specific construct pertained to the formal management of risk in the construction industry.

18.4.5.3 Risk assignment

Social contagion has been seen to be beneficial in allowing the design team to 'hold' the uncertainty associated with innovative aspects of the design. However, this social phenomenon may have masked the need for a formal assignment of the risks. As a result assignment of the risks was considered too late in the process for issues of liability to be resolved within the project programme. Reflecting on this issue ARCH(A) is recorded to have commented, *'And I think (..) at one point we were asked whether we would take on the risk <u>- and **that** I didn't feel comfortable with of course</u>, so/ but I did think that <u>it was unclear where the risk/who the risk was going to lie with</u>. And it was clear the local authority had decided that they weren't going to and Ramboll weren't going to, so (.)'*

The main contractor made a similar point saying *'but regrettably I think it has all come back to risk (.) being risk averse and shedding risk onto other people, which is (.) you know, I mean that is fair enough if (.) it is all done on liability nowadays isn't it //* (lines 105-108).

ARCH(A) and ARCH(B) reflected together on whether a different client would have accepted the risk in the case of this innovative technology.

[ARCH(B)]: *'Do you think a private client would have taken the risk?'* [ARCH(A)]: *'Yeah I think they might have it does depend on the type of contract and things, but I think that if (.) you know if the school had been the only client, they would have gone for it, they would have taken that risk'* (lines 62-71).

Strategies for managing risk include: risk mitigation, risk acceptance and risk assignment. The party to whom the risks are ultimately assigned need to mitigate the risk to a level at which they are able to accept it.

The fourth emergent construct regarded how projects are procured in the construction industry.

18.4.5.4 Procurement route

The fact that the floor of the new building was not laid until sixteen months after the decision to withdraw the lime-pozzolan concrete specification at Stage D, suggests that it was the procurement process, rather than the programme, that prevented any further substantiation of the novel technology.

Both the architect and the main contractor reflected critically on the procurement process in the case of this project. Talking about the Design and Build procurement route the main contractor commented:

[M.CON(A)]: *By shifting stuff over it means we've then got to employ an architect, we have got to employ a structural engineer, M & E consultant and all those other guys were actually already in place. Yeah, that is probably me just having a general whinge about (.) I can't actually see that it makes sense. You know, financially it doesn't, because you are paying twice for a lot of it, it pushes the price up. They have paid all of the design fee's and just to kind of duck that last bit of risk, they then get us to build in all our design fees and indeed… I can't actually see the sense in it myself, I think it just makes it more long winded, more protracted, difficult, you know endless* *email trails because you are having to tell people little bits and bobs of (.) oh by the way reference that gap this is what we have done and they go back to their consultants to see, are you happy with how they filled the gap that you left (.) so you know (.) it is not the way I think is the best way to do a job. But that is the way it is going generally I am afraid (.) on the bigger ones* (lines 108-115).

The architect suggested that had the design team been able to continue the design further, that further testing might have been possible.

[ARCH(B)]: //*I was going to say// this is also a Stage D tender, if we had gone on extra stages //*[ARCH(A)]: *I know//* [ARCH(B)]: *there might have been time to test things (.) further on a big scale maybe //*[ARCH(A)]: *Yeah//.* [ARCH(B)]: *I think there is a great risk of losing things when you tender so early* //[ARCH(A)]: *Yep // with a greater degree of uncertainty. And that has happened across the board for us* (lines 203-207).

[ARCH(A)]: *Because as it happened it was a best part of a year/ well it was over a year from being appointed to going to tender, due to planning issues and various things, but if we had known that we could have even done a large scale test within another space in the school.* //[ARCH(B)]: *Yeah// They could have lived with it for a year, just seen what it was like, so that*. (lines 209-213).

18.4.5.5 Implications of implementation being contextual embedded

The contextual nature of design is what Ivory (2005) describes as 'the unique politics of each project's makeup'. The unique nature of individual projects precludes a formulaic management strategy, rather demanding a flexible management approach that can respond to dynamic circumstantial and political factors, which are in a constant state of flux.

18.4.6 Theory 6: Implementation processes are initiated

This theoretical assertion emerged from the relationship between three constructs identified from the case-study data – technology coupling, embodiment of the design philosophy and representation. The relationship between the three constructs is illustrated in Figure 35. In this section the three constructs are first explored individually, with reference to the extant literature, and then the implications of this emergent theory are discussed.

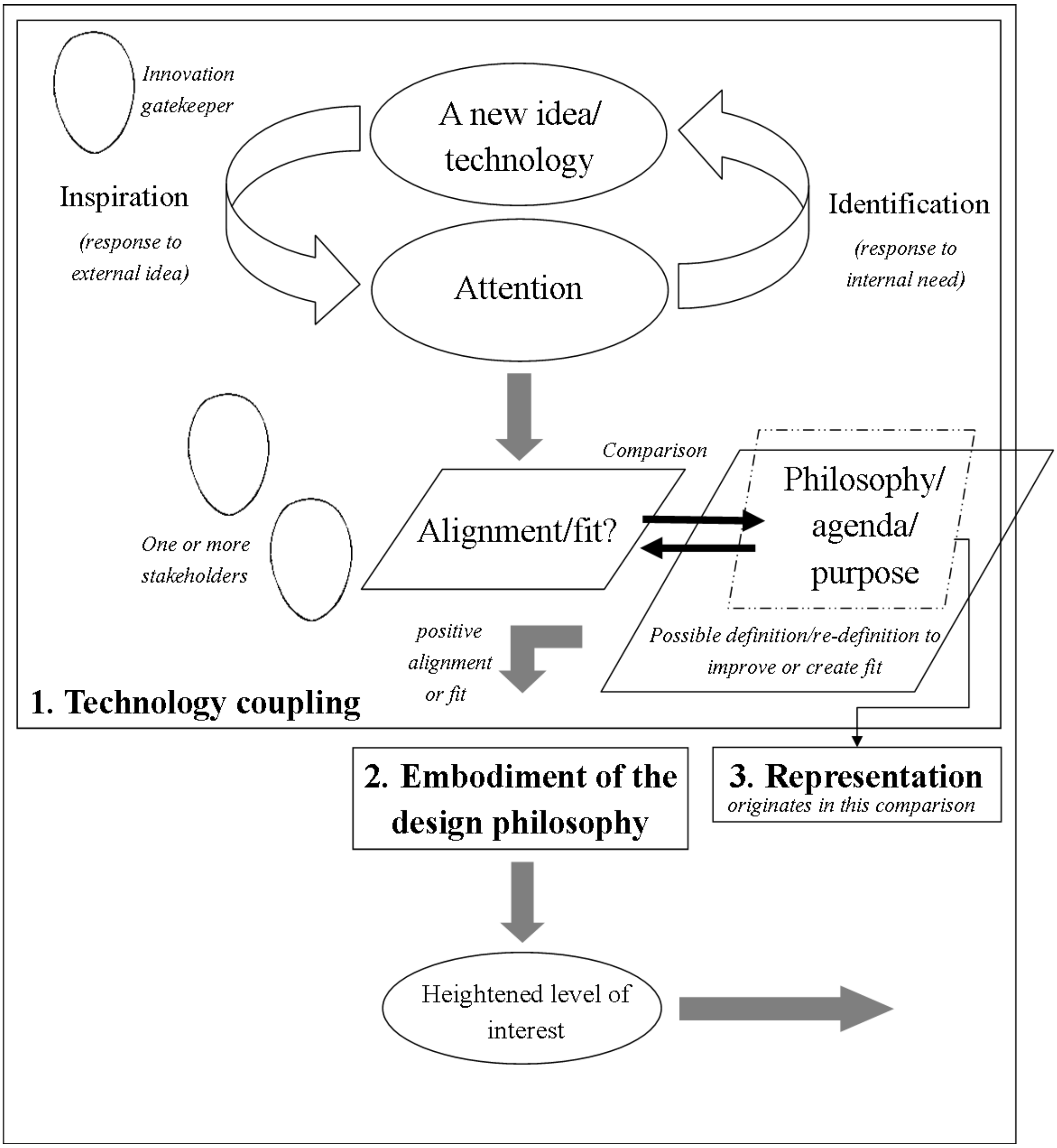

Figure 35: Initiation of the implementation process (Theory 6)

18.4.6.1 Technology coupling

In this case study the implementation process was observed to be initiated by a 'coupling' of a novel technology and a project design team. This construct was supported by Freeman (1974) who argues that 'innovation resembles a coupling process but it is of a particular nature since the two elements brought together, the market and technology, evolve in an unpredictable way'.

Specifically in the context of the construction industry, Ivory (2005) describes this as the ‘brokering of technologies form consultants to clients’. In this case the initial ‘coupling’ process was not technology specific; rather the client was seen to be *inspired* by the prospect of doing something innovative (lines 5-20).

[SLT(B)]: *Erm...Well I suppose from the beginning, the idea of you working as a researcher on the project seemed like a really great idea and it was actually mentioned at the interviews first of all and it was not something that I’d really considered to be honest Ellen, that we would have any research going on with the project, and actually I thought, that in itself was quite an exciting idea. And it really fitted with the notion of innovation and at the time it was [ST.ENG (B)], I think wasn’t it, it was [ST.ENG (B)] who, was there and who was discussing that possibility with us...and I guess, do you know I don’t know if I really understood too much about what that meant, but I knew there was some work going on at the University, we talked about kids getting involved and that seemed like a good possibility, so all of that kind of thing, there was a lot of interesting promise, but I suppose I didn’t really know or understand what that meant, other than, erm, it was the opportunity to try out something new I suppose, something that hadn’t really been done before and for us that seemed to fit with what we were aiming for within the project really’*

In contrast, Slaughter (2000) suggests that the implementation of innovation begins with ‘*identification of the potential alternatives’*. *Identification* and *inspiration* may both be antecedents of ‘technology coupling’ but identification puts an emphasis on the search function and implies that novel ideas are sought out from within the system, in response to identified needs. Inspiration, on the other hand, implies that ‘technology coupling’ is, at least sometimes, less premeditated and prompted by external source of novel ideas.

It emerged from this analysis that technology coupling, by inspiration or by identification, is the primary mechanism for initiating the implementation process, as is illustrated in Figure 35.

In this case study, Ramboll is believed to have been what Slaughter (2000) describes as the innovation ‘gatekeeper’, ‘the individual/organisation able to identify new alternatives'. Certainly the 'technology coupling' process was reinforced by the opportunity for the researcher to give the project architect a tour of the Centre of Innovative Construction Materials (CICM) at the University of Bath, during which a number of specific material technologies were discussed. In this way the doctoral research-programme, itself, played a significant role in the process. Although, the unique, and thus rather artificial, nature of academia-industry collaboration fostered by the EngD programme, may preclude generalizable findings, this project has demonstrated that there is a role for academic-institutions in the coupling of innovative construction technologies with 'real-world' projects

From analysis of the case study it emerged that the initial inspiration/identification conceptual 'hook' is only the first stage of the technology coupling process, the second stage being an 'alignment' check that is argued to be undertaken by the project stakeholders more or less consciously. In the case study, once the school became aware of the possibility of doing something innovative (utilising innovative materials); doing so became part of the school's agenda for the project. The innovative aspect of the project was an attractive prospect at this early stage because it fitted with the school's values, 'inspiration, innovation and inclusion' (school website).

Although SLT(B) refers specifically to this 'fit' in line 10, this theoretical construct only really emerged from consideration of the relationship between technology coupling and the second theme 'embodiment of the design philosophy'.

18.4.6.2 Embodiment of the design philosophy

Applied innovation became part of the design philosophy of the project from the outset of the design process, the school having been inspired at the consultant interview stage. The school were understood not to want just another building; they wanted a building that would inspire the pupils, which would be a testament to research and what can be achieved.

For the school the implementation of an innovative solution promised to be a demonstration of the power of being in 'inquiry mode' in the 'adult real world', SLT(A): '*...if we are truly going to be organisations about encouraging people to...explore, innovate [erm]...inquire really, just that sort of being in inquiry mode, that is the reality of being in an inquiry mode in the adult real world, it does mean* *taking risks, it does mean it may not go to plan, or from plan a to b to c to d to e. So again I think that is an interesting concept...*' (lines 92-95). The school were keen to demonstrated and instil in the pupils the value of exploratory and inquisitive research, SLT(A): *'what we would like for young people, is that research, and ourselves as adults in the school, is that research element should just be very much part of our daily practice'* (lines 102-103). In this way, the building was anticipated to 'do' something for the pupils using it, SLT(A): *'I was excited by the product coming out...really felt hopeful about what that could do for young people, was very excited that we could be part of something being developed and new… all of those things have been really <u>really</u> exciting'* (lines 37-40).

Specifically this innovation story was believed to have the potential to *'bring the curriculum alive',* SLT(A): *'I know for some people in the curriculum, and some young people would find that* (the facts and the contents and the measurements) *fascinating and it's a real experience that they could work on, and just brings the curriculum alive and the joy of learning alive' (lines 63-65).*

Two further utterances explicitly suggest that the lime-concrete floor was perceived to embody the design philosophy of the project. Talking about the omission of the limecrete floor SLT(A) is recorded to have said, '*Now I'm not saying the building won't be amazing //yeah// you know this is one element of it, but it was just that, that was everything we were about'* (lines 99-100). This notion that the floor being 'what the project was about' is reinforced by ARCH(B) in the following exchange

[ARCH(B)]: *It was a shame because it's a piece of proper innovation.*
[ARCH(A)]: *Yeah - //which was what the whole building was supposed to be about.//*
[ARCH(B)]: *//which would have been really good for the whole building.//*

The following comments, from the follow up interview with SLT(A), imply that the lime-concrete, as well as the other sustainable materials, notably the CLT and the rammed earth, defined the 'character' or the 'core' of the building, SLT(A,2): *'(.) I think we are still comfortable that it holds to its character even though we have had to lose some of our passions - such as the limecrete.'*

[SLT(A,2)]: *And (..) from our learning perspective it is still true to its core. Frustrating losing some things like the limecrete and the other innovative bits, but we have still maintained some, so we have got the rammed earth. We are still using some* *of the stone out of the ground in our visible landscape which is good (..) and the CLT I think will still be very true to seeing a building's engineering in practise - so I think that that is really nice* (121-126).

In this project the school spearheaded the design brief. Although representatives of the Local Authority, the client, were actively involved in the design process, only the omission of the innovative lime-pozzolan concrete floor at RIBA Stage D revealed the misalignment of the school's and the client's requirements. Specifically, LA(C) is noted in the researcher's fieldnotes to have said, "We're a Local Authority, not someone looking to innovate" *(secondary data).*

The process of 'technology coupling' raises questions about impetus for the implementation of novel technologies and ultimately whose agenda it was serving? It is acknowledged that the pursuance of applied-innovation on this project was beneficial to the engineering consultant, for as Ivory (2005) points out 'if consultants want to develop their competencies and their market reputations they must find (or construct) clients that are willing to allow them to develop and to 'try-out' new design innovations within their projects'. However, in this case, when it was suggested that suggested that Ramboll had been 'pushing the agenda of innovation', the school expressly denied it, SLT(B): '*it was implied that Ramboll were pushing this agenda of innovation with the building you know, and <u>actually that was not the case at all – you know, this is about what we the client wanted right from the start'</u>* (104-106).

Ultimately a design-team's commitment to innovation is fostered by the alignment of multiple agendas, which need not be the same as long as they are harmonious. Speaking about the perceived commitment to the implementation of the novel lime-pozzolan concrete floor in this case study ARCH(A) commented:

[ARCH(A)]: *I thought we would have followed it through, because <u>I thought that everyone involved was very committed, so whether that be</u>* <u>(the local authority)</u>*<u>, the school were clearly very committed throughout.</u> Obviously Ellen and Ramboll were doing a great job of investigating things, so I think I always (.)'* (lines 10-14).

Reflection upon her experience and speaking about the level of commitment required to bring about innovation, SLT(B) commented, '*You know it is just like...you kind of feel as though, in the end to get something <u>done a lot of people have really got to care a lot and fight a lot for it'</u> (lines 109-110).*

The third theme identified from the empirical data was representation. Although this is a construct that is believed to develop during the process, it is recognised that representations is likely to be conceived in the initial alignment check, when then the stakeholder's broader agenda or philosophy or purpose is first considered alongside the innovation. The word 'purpose' is defined as *'that which a person sets out to do or attain, a determined intention or aim'* (Dictionary, 2014b). Engineering-design is a manifestation of the uniquely purposeful nature of human existence.

18.4.6.3 Representation

The propensity of humans to create and assign meaning through symbolism is thought to make representation an integral part of purposeful action. Representation is theme emerging from the interviews with SLT(A) and SLT(B). For SLT(A) the innovative lime-concrete floor had, at some level, come to represent 'the reality of the project', *'almost that moment was the peak excitement, and it probably represented the reality of the project, more than just a floor'* (lines 13-14). It is thought that this viewpoint may have been fostered by the lime-concrete and the rammed earth samples, which were the tangible manifestations of the final building during the design process.

The lime-concrete floor is also observed to have become representative of the project story. The following three excerpts, suggest that the development of the lime-concrete, a narrative with its own highs and lows, had come to reflect the wider project story:

[SLT(A)]: *'This limecrete floor has been an emotional roller coaster. So I guess it has kind of represented a lot of things beside just the very particular limecrete product'* (lines 6-7).

[SLT(A)]: *'all those frustrations around planning and all those kind of things…. it's really interesting how <u>it mirrored that journey of the highs and lows of any project, this was a very physical representation</u>'* (lines 23-25).

[SLT(B)]: '*<u>and this is not just the building</u>, it's about- you have an ambition, you have a place where you want to go to, you think oh well I'm not actually going to get there, so what can I retain from the gem of what we dreamt of and thought of that will still actually meet that in some way or another'* (lines 62-65).

As a result of this representation, broader frustrations were observed to come to bear on this specific novel aspect of the design. The excerpt in lines 32-35 suggests that disappointment over the floor, not only brought to mind project-specific frustrations, but perhaps also wider dissatisfactions in the ‘bigger world’, SLT(A): *‘just that in that bigger, safer world of routine, how hard it is to make spaces for what aren’t huge risks, and sort of really push some of these questions about us as a school making that journey, and independence really and about how much do you want something, so the limecrete represented so many things for me, that I found it fascinating’* (lines 32-35).

Clearly SLT(A) was able to appreciate that she had pinned additional weight on the limecrete as a product for in line 37 she says *‘but for me to talk about the limecrete itself, it’s quite a kind of small experience, I was excited by the product coming out...’.*

Furthermore the innovative lime-pozzolan concrete floor is also seen to have been attributed a degree of existential representation, SLT(A): *‘you can still achieve something from the ground becoming our surface so it kind of held the bigger purpose of ‘how do we turn things from our own ground into something that we can all relate to, such as a floor covering’* (lines 27-29).

Schön, (1992) writes *‘The designer not only visually registers information but also constructs its meaning – identifies patterns and gives them meaning beyond themselves’*. The propensity of humans to create and assign meaning through symbolism, is the central tenant of symbolic interactionism, which became a branch of social research in the later part of the nineteenth century. Symbolic interactionism purports *‘that objects and events have no intrinsic meaning separate from the meanings people assign to them in the course of everyday action’* (Prasad, 1993). In his study on the implementation of computers in the workplace, Simon (1965) argued that the new computers reflected individuals *‘hopes, anxieties, dreams and inadequacies’* in Prasad, (1993). In this project the disappointment expressed by SLT(A) and SLT(B) was perhaps the result of the shared symbolic meaning that they had attributed to this innovative lime-pozzolan concrete floor.

18.4.6.4 Implications of implementation processes being initiated

From a managerial perspective it is less interesting to observe that implementation processes *are* initiated, than to make the theoretical leap and assert that implementation processes *need to be* initiated. Certainly Bürgermeister’s (2012) reference to ‘innovation triggers’ and ‘innovation impulses’ would suggest that the initiation of innovation process is a valid phenomenon to have observed. The observation that inspiration or identification are antecedents of technology coupling, closely echoes the generally accepted technology-push, market-pull model and supports time spent engaging with the frontiers of science and technology and/or the client’s brief in ‘an alert manner’ (Bauer et al., 2012).

The second stage of the technology-coupling process, alignment with individual purpose or philosophy, is thought to be less familiar, but not unrecognised in innovation literature. Consider for example the artistic approach to ‘Innovation Work’ promoted by Böhle, Orle & Wagner (2012). Unpacking the way an artist sets about a new piece of work, one of the features they distinguish as characteristic of the ‘artistic approach’ is that artists generally act out of personal concern or interest, ‘they have an individual reason to take action without it being completely tangible’. This is certainly a complementary theory, as it puts a similar emphasis on the role of individual values as a stimulus for creative action.

The impetus that has observed to emanate from alignment with personal goals or philosophy is a compelling argument for not compartmentalising professional work from individual values. Bauer et al. (2012) go further still in purporting that one’s ‘innovation competence’ is increased by ‘combining one’s inner interest with one’s work interest’.

Theories 7, 8, 9 and 10 are thought to be highly interrelated. The nature of the relationship between these constructs is depicted in Figure 36. Theories 7, 8 & 9 are considered in turn and then the emergence of theory 10 is discussed.

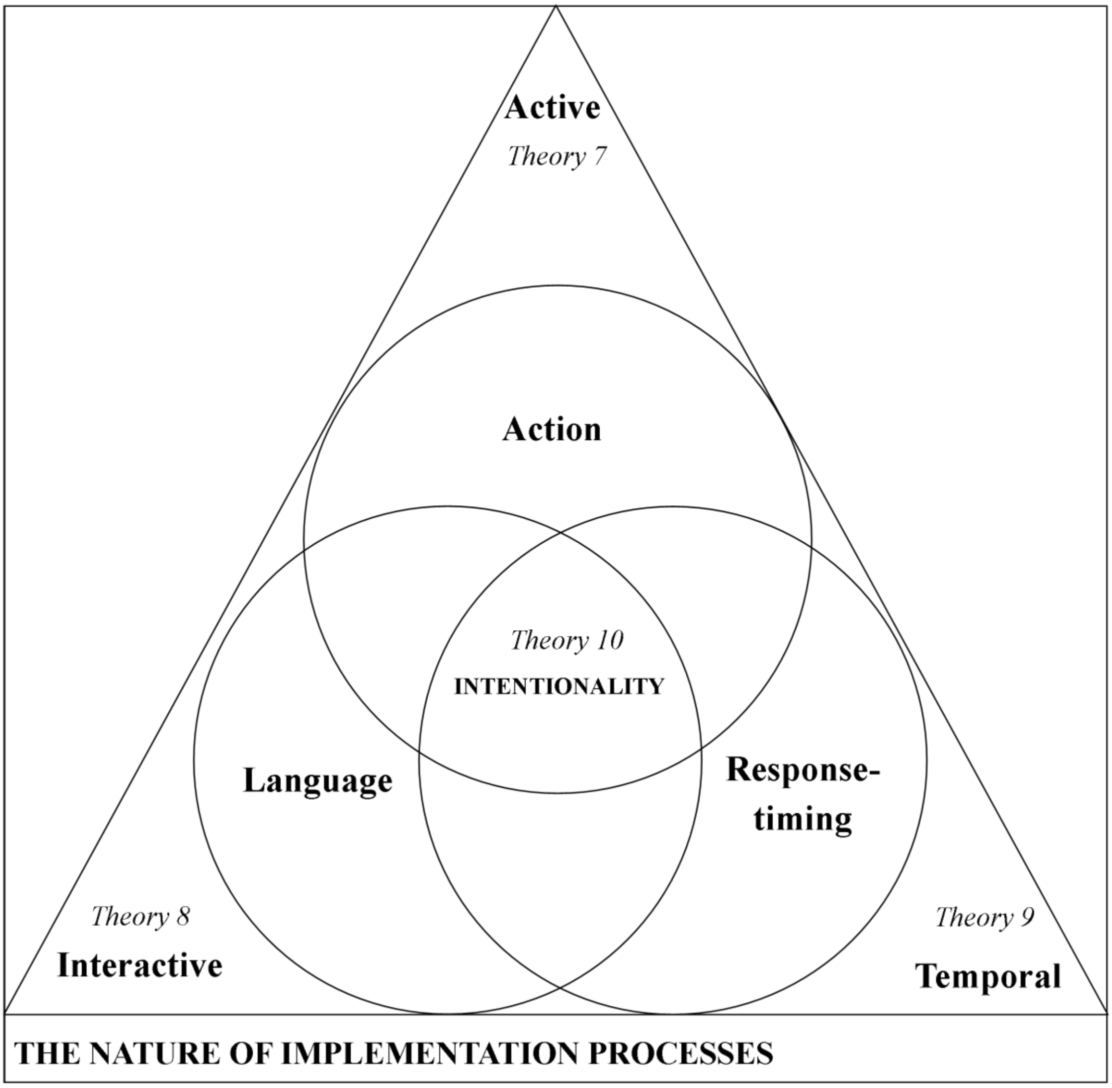

Figure 36: Implementation as an active, interactive and temporal process

18.4.7 Theory 7: Implementation is predicated on human action

It has been observed that implementation is predicated on human action. It is action that differentiates the *implementation* of novel technologies from the *adoption* of novel technologies. Implementation has deliberately been differentiated from adoption in this study, for it is possible for innovations to be adopted hypothetically and not implemented. Whereas, the innovation-adoption process terminates with the decision to adopt, or not adopt a novel technology; the innovation-implementation process additionally includes the post-decision period. In this study, the implementation process has been assumed to be complete with realisation of the innovation, specifically construction of the rammed earth wall and erection of the CLT frame. This is different from Slaughter's (2000) model of construction implementation, which includes an evaluation phase. In this research project data was not collected on the evaluation stage due to programme constraints.

In this research action has been defined simply as ‘mobilised-decision’. Action may be indirect, lifting a phone to request or sanction action on another individual’s part, or constitute direct personal endeavour. The action may be pro-active or reactive, but either way ultimately someone, somewhere must be motivated, or compelled, to apply themselves to realising purposeful ends. In the case of the implementation of innovative technologies these *ends* are future constructs, products of human imagination, laden with the intrinsic uncertainty of the future and threated by unforeseen challenges and unintended consequences.

Due to the scale of construction activity and the de-mechanisation of many sustainable methods of construction, the implementation of sustainable construction materials almost certainly demands considerable exertion on someone’s part. In this case study numerous examples of strenuous activity can be identified on the part of numerous individual actors: production of the rammed earth samples in the lab (researcher), excavation of half a tonne of limestone (contractor assisted by an excavator), manual sifting of half a tonne of limestone (researcher), diamond polishing of the lime-concrete sample panels (specialist sub-consultant) and manual grading of several tonnes of site earth (main contractor). Action is the essence of what Rohracher (2003) describes as ‘learning by trying’.

Not only is the case-study story beset by examples of individual actions, but ‘agency’, which Garud (2010) defines as ‘the ability of individuals to act in the world’, was one of the constructs that emerged from the interview data.

18.4.7.1 Part client and agency

One feature that was observed to have added to the complexity of the case-study project was that it was never clear to the design-team who the client was. In this case the local authority was procuring the new school building and was contractually the design team’s client; however the school, as the end user, was perceived to be driving the project-brief. The following excerpt (lines 67-73) provides evidence of the school's position:

[SLT(B)]: *'I think the thing is, <u>because we are clients</u> <u>we are not really in control of this work</u>, that is the other really frustrating thing Ellen, you know that <u>there are these other bods who are the signers off of the money</u>, who basically say oh you know it's a school, health and safely paramount, wasn't really tried and tested, can't do it, takes too long to set, you know, takes too long, too much risk for the builders no no no, and that is partly what has driven us to become an Academy is <u>that real frustration that other people, sort of vetoing your desires</u>'* (lines 67-73).

SLT(B)'s opening comment '*because we are clients we are not really in control'* is highly incongruent, as typically being a client is tantamount with being in control as the decision maker. Believing they were the clients the school had evidently misinterpreted their agency in this design process.

Human agency is the ability of individuals to act in the world and an appreciation of agency, be it conscious or sub-conscious, is fundamental in prompting all human action. (Garud et al., 2010) purport that, *'it is agency that empowers decision makers to choose paths that determine the future and to create paths that transform it'.* Omission of the lime-concrete floor was an example of the local authority 'vetoing the schools desires' and reinforced to the school their lack of agency.

SLT(B)'s comment in line 72 and the excerpt in lines (76-80), provide evidence that the local authority's decision, to request withdrawal of the lime-concrete floor, was significant in the school's consideration of becoming an Academy. Academy schools receive funding directly from the Education Funding Agency (EFA), rather than via local authorities, giving schools 'freedom from local authority control' (Department for Education, 2013).

[SLT(B)]: '*so I think actually in some ways <u>it's just led us to thinking in the future we want to do these things ourselves</u> you know and we'll get our governors to underwrite any risk and now that we have learnt about what's possible that is where we want to go in the future and not just be told by people, other people – who assume that they know more than we do and we always assume that because that is their professional job to do so'* (lines 76-80).

The importance of agency is underlined by fact that in August 2012 the school did indeed opt to become an Academy, before completion of the project. SLT(A,2) spoke about the challenge of this transition in the follow up interview, saying *'we have gone through a very stro (.) because we have now become an Academy during the time as well. <u>The client is now us</u>. // interviewer: Oh okay// And of course, we we'd sort of (.) you know (.) // Yeah // wish you kind of (.) so really (.) but trying to get that ship turned round to face us now is quite hard* (lines 90-94). In lines 141-144 SLT(A) explicitly refers to the former 'confusion over the client' saying, '*it was a bit of the red pen without our (.) again this (.) again our desperate desire to become an Academy to stop that kind of practice. And I think there is various (.) a few other things that have happened like that that we are only just discovering now. With this confusion over who was the client (.) Is it us or is it them*?'

From this case study it is clear that it is vital to know where decision-making agency lies.

SLT(B): *'SLT(A) and I were sat in here and we were thinking – what are we going to do about this? and it was like you couldn't ...you couldn't ...it was like you were trying to fight somebody with your arms tied behind your back, it's really really difficult, so yeah'* (lines 158-162).

18.4.7.2 Implications of implementation being an active process

The active nature of implementation demands efforts to create and maintain the conditions necessary for individual action. Ive (1995) writes 'Innovation, like murder in a properly made who-done it, requires the coincidence of means, motive and opportunity in the same party'. The categorical trinity –means, motive and opportunity, is a structure used in criminal law courts to assess the culpability of a defendant. It is argued that all human action demands the coincidence of means, motive and opportunity. Means is the wherewithal to bring about the desired result and might typically include tangible resources (factors of production) and the necessary capability to use them to realise the intended outcome. Motivation is typically the rational for embarking on the change; it provides the energy that drives the process. Opportunities create the chance to do something, they're openings made possible by a favourable set of circumstances. Given the active nature of implementation makes it contingent upon the coincidence of means, motive and opportunity, the attention must be given to creating and maintaining each of these enabling conditions.

One specific example emerging from this case study is the importance of the implementation project featuring as a recurring agenda item at the design team meetings. This basic act proffers a degree of significance to the progress of the sub-project and creates time within the context of the design meeting to discuss any matters arising, including any resources required.

The theoretical assertion that implementation is predicated on human action demands a greater emphasis on human agency, that is ‘the ability to act in the world’ (Garud, 1997). Individual agency, or the perception thereof, will inevitably vary from person to person and may be difficult to leverage at an individual level. However, the notion of agency as an emergent property of a complex relational system (Garud, 2010) is arguably easier for managers to exploit by encouraging creative and autonomous action.

The theory of ‘effectuation’ is argued to be attractive in facilitating implementation and technological change, as it puts emphasis on human action as ‘the predominant factor shaping the future’ (Brettel et al., 2012). Effectuation affirms human agency and taps into the intentional, social, experiential, existential and effective nature of human action.

18.4.8 Theory 8: Implementation is an interactive process

A focus on language, in the selective-coding of the design team meeting transcripts, has demonstrated that language is used to propel and steer implementation processes in design.

The use of De Bono's (1999) ‘Six thinking hats’ as a selective-coding framework has been effective in identifying how utterances of different ‘colours’ affect the course and energy levels of the design dialogue in different ways. For example, alternating ‘green’ (*ideas, options, possibilities, routes and alternatives*) and ‘yellow hat’ (*speculative-positive, proffered optimism*) sequences have been seen to build energy levels up, whereas ‘black hat’ utterances (*difficulties, problems, dangers, obstacles, downsides, weaknesses, risks*) bring the energy levels down. ‘Black hat’ utterances have, however, been seen to be effective in driving the design process forward by closing down surfeit options and thus helping converge on a solution (see DTM03).

Language not only affects the process but also the outcome, with language used to talk-in and talk-out aspects of the design, (see DTM05). This empirical observation supports Rohracher's (2003) assertion that innovations are ‘shaped, stabilized and socially embedded through language.’ Negotiation skills were shown to be a powerful tool in design processes (see DTM06).

It has been observed that language is also powerful in dispelling or aggravating uncertainty in design processes. Specifically, design-intent, or a lack thereof, is communicated through language. For example, ‘red hat’ (*feelings, emotions, intuition, values*) utterances have been observed to be poor at communicating design-intent (see DTM04 and the discussion in Theory 10). Actions were seen to be far more effectual in communicating design-intent than language (see Theory 10).

Language also provides insights into heuristic decision-making processes in design (see DTM02). Exposing individual heuristics can allow otherwise subconscious cognitive processes to be challenged and thus exposed to alternative logics.

18.4.8.1 Implications of implementation being an interactive process

The theoretical assertion that implementation is an interactive process advocate’s face–to-face communication in design. Although this case study has considered both verbal and written communication, the observed influence of linguistic and prosodic aspects of face-to-face interaction in steering design processes implies this is an indispensable feature.

Given that sub-conscious mental processing can either enable or impede implementation processes, linguistic features that surface assumptions (particularly metaphors), are asserted to be worth recognising and consciously interpreting or challenging, both in one’s own discourse as well as that of others.

In everyday conversation language is used and interpreted below a level of human consciousness. Given that language has been observed to be so powerful in design processes an increased awareness of the authority of language in design, could prove advantageous in guiding design processes and realising desired outcomes. Specifically it could be valuable to appreciate how utterances of different ‘colour’ (De Bono, 1999) influence the energy levels and course of the conversation in design as well as to be conscious of aspects of the design being talked-in or talked-out of the scheme in conversation.

18.4.9 Theory 9: Implementation is a temporal process of human activity

Adoption of innovative technologies is contingent upon novel ideas being admitted into and then retained within the 'solution space' during the 'divergent' and 'convergent' processes that are characteristic of design (Jones, 1970). It has previously been shown that the 'divergent–transformation-convergent' form of design processes is demarcated by transition events and that the behaviour of groups working on projects is subject to 'temporal pacing' (Gersick, 1988). In this case study transition from divergence, to transformation, to convergence during the project design process was implicit, but was identified by subsequent analysis of the design team meetings.

In this case study, because the implementation of sustainable materials was a desirable rather than an essential aspect of the project, the applied-innovation process was undertaken in parallel with the main project process. The 'temporal pacing' of the two concurrent processes was observed to be mutually constituted. The presentation of the rammed earth samples is accredited with prompting the evaluation process characteristic of the 'transformation stage' and ultimately formal project milestones, such as the issue of tender documentation at the end of Stage D, demanded the substantiation of the novel lime-concrete to be sufficiently complete.

The implementation process in this case study was seen to be susceptible to temporal effects (interruptions, lags, lulls and holdups). Centralised agency is one cause of temporal vulnerability, resulting in processes dependent on external authorization or resource allocation. In this case study, the documentary analysis highlighted how the research and development of the bespoke lime-pozzolan was interrupted by the need for additional limestone to be extracted from the school site. This was thought to have introduced a two-month delay into the concurrent research and development process. An extra two-months would ostensibly have allowed additional testing to have been conducted prior to the tender issue in February 2011. In the context of human activity systems, initiatives, such as innovation, are often vulnerable to human limitations including the lack of, or diminishing, attention or impetus, which can disrupt or impede temporal initiatives.

One construct pertaining to implementation as a temporal (and active) process is the observation that innovation is contingent upon grasping opportunities.

18.4.9.1 Opportunity grasping

Reflecting on the nature of the experience, SLT(A) commented on a sense of lost opportunity, in lines (74-75), *'so a slight sense of is there lost opportunity there, is something I'm holding'.* This was obviously something she continued to hold as it was a sentiment she repeated in her second follow-up interview, SLT(A,2): '*I just get that slight sense of lost opportunity there - inspiring for the future (.)'* (lines 127-128).

Reflecting on the challenge of grasping opportunities in the school context [SLT(A)] expanded on this issue, [SLT(A)]: *'so a teacher who's so caught into a timetable and once a term starts, you know that sort of motor is running and it's very hard to squeeze in and get these golden nuggets of opportunity that come along'* (lines 53-55).

The lack of opportunity to innovate in the school context, which is thought to closely mirror the industrial design context, is evidence of a broader problem in what (Thiele, 1997) describes as our 'age of hyperactivity'.

[SLT(A)]: *'and I know [T(A)] was hugely excited by it, but in terms of <u>the machine, that sort of authority, size of the curriculum banding on at its own pace</u> to meet, just to meet the sort of curriculum requirements of taking an exam at this point, that tension between <u>how do you make the most of a nugget</u>, without it taking over the core requirements of what your trying...<u>how do you make space</u>, so that experience has been an interesting one,* (lines 54-58).

The questions 'how do you make the most of a nugget of opportunity?' and 'how do you make space?' are thought to be pertinent across a range of domains.

[SLT(A)]: *'it's just an opportunity comes and how we as a school, or a teacher could just grasp an opportunity when it comes, take enough from it without it being as all-consuming as sometimes something like that would require…'* (lines 66-68).

[SLT(A)]: *'So that's interesting for me, how do you, if we had that...if we ran that time again, how would I make that more possible, or what is it about our school day structure, that makes that so hard, for a teacher to stop'* (lines 68-70).

[SLT(A)]: *'how does the curriculum side make space for unplanned gems. And I don't know the answer to that at all, but some of it is about our school* day *and just the pace, and is there space for creative...'*.

Hillson (2002) and others characterize opportunity as ‘upside risk’ and argue that opportunities can be managed by modification or extension of familiar risk management processes. Uncertainty is conceptualised as an umbrella term, capturing both risks ‘uncertainty with negative affects’ and opportunities ‘uncertainty with positive affects’.

18.4.9.2 Implications for implementation being temporal process

Applied-innovation in construction is generally going to be concurrent with delivery of a primary construction project. The temporal nature of implementation makes it appropriate for the process to be regarded and actively managed as a supplementary sub-project, incorporated in the main project programme to ensure integration of key activities and decisions.

A proactive approach to managing project opportunities is argued could ‘maximise the probability and consequences of positive events’ improving project outcomes and realizing benefits. Hillson (2002) recommends a formal approach, suggesting that opportunities are identified by project teams in a similar way to risks using brainstorming and similar tools. These could be recorded in an ‘opportunity register.’ The familiar hierarchy for appropriately dealing with different risks ‘avoid, transfer, mitigate and accept’ could be modified to ‘exploit, share, enhance and ignore’ (Hillson, 2002). As with risks, opportunities could be allocated to individuals owners and meetings put in place for reviewing and reporting their status.

Theory 10 emerged from the evident interrelationship between theories 7, 8 and 9.

18.4.10 Theory 10: Language, action and response-time are markers of intentionality in human processes

One phenomenon that emerged from this case study is that language, action and response-timing are markers of intentionality. These ‘markers’ are not thought to be consciously placed as signposts signalling intent, but to be continuously and intuitively interpreted as indicators of the intent implicit in others.

The notion of ‘intentionality’ supposed to be similar to Slaughter's (2000) description of an organisation’s *commitment* to innovation. It is however argued that commitment is highly problematic in the face of uncertainty and therefore difficult to secure in the context of innovation. When trying to decide whether or not to pursue the testing and development of the bespoke lime-pozzolan concrete, it was not possible to secure the design team's commitment, for this solution may not have proved technically feasible, but it was necessary to secure the design team's intent, to justify further investigation into the technical feasibility of this solution. The distinction between intent and commitment can perhaps be appreciated metaphorically, by considering the social customs of engagement and marriage.

It is recognised that human language is substantively vague, with natural conversation riddled with vague predicates (tall, red, bald, heap), adverbs (quickly), quantifiers (many) and modifiers (very), which are interpreted by the listener in context (Keefe & Smith, 1999). In design team meeting 04 (DTM04), which was revealingly entitled 'Why are we discussing this? Because of the possibility of using it or are we going to use it, or are we not sure if we are going to use it?', a high degree of interpretive-uncertainty was encountered. It was observed that a lack of clarity about the design-intent inhibited further design-development. The implications of this observed phenomenon are expressly discussed in Theory 11). It is asserted that the language communicating intent was in this instance perceived to be too vague to enable further action.

Figure 37 (a) is a theoretical framework, designed to illustrate how language is used to signify intent in everyday communication.

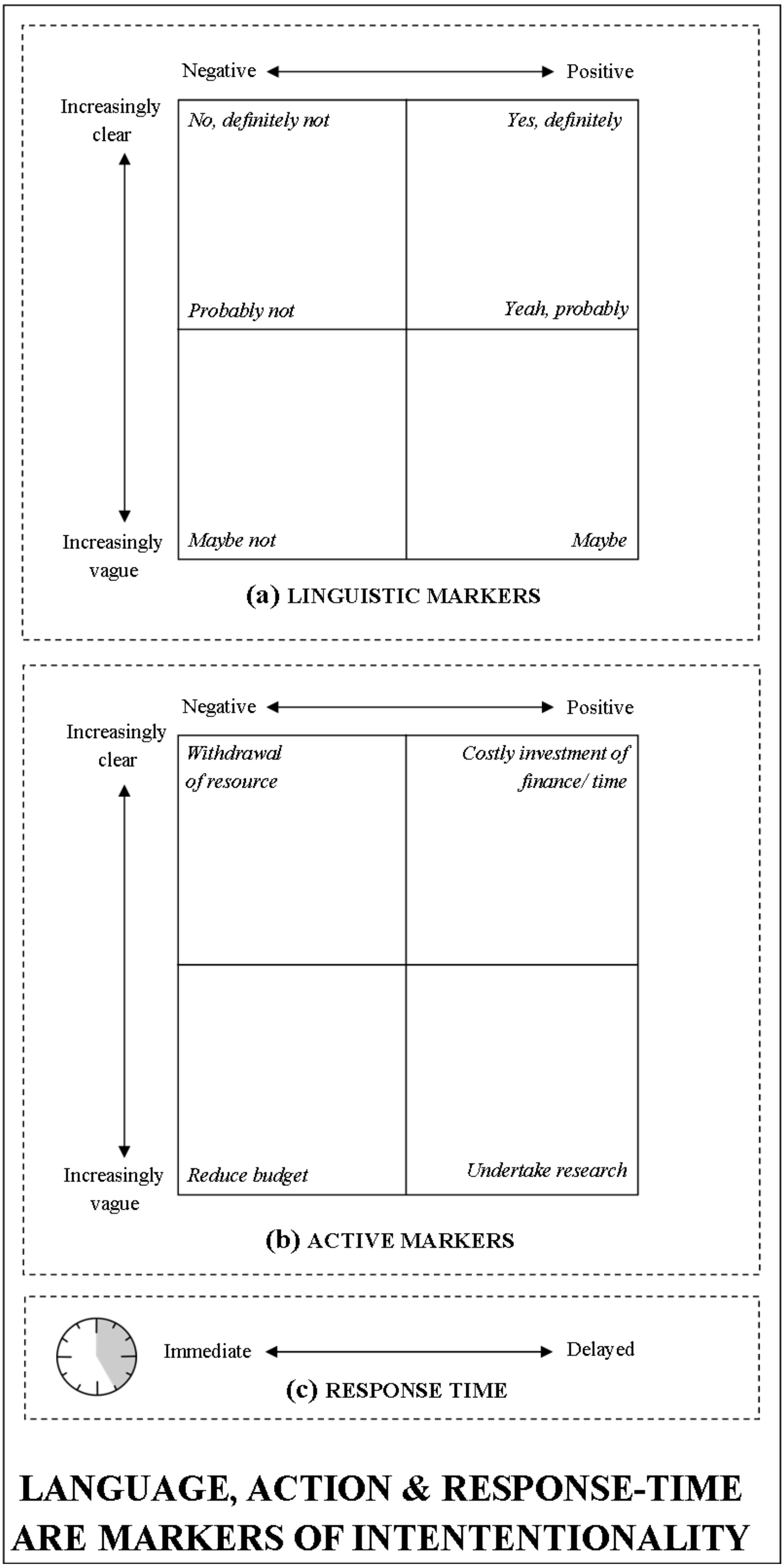

Figure 37: A theoretical framework for plotting markers of intentionality

One caveat of this representation is that the interpretation of language performed subconsciously is considerably more sensitive to prosodic aspects of communication and to individual variation that could ever be tabulated. For example, when asking ‘will I see you later?’ one deduces whether a friend’s ‘yes probably’ is likely to be a yes or almost certainly a no, from ones experience and more importantly one acts accordingly.

Action is purported to be clearer marker of intent than language, although it is recognised that actions can equally be more or less vague. Going back to our example, had the answer to the question not been ‘yes probably’ but rather ‘yes, I’ve booked my ticket’, it is thought one is more likely to go ahead and do likewise. Figure 37 (b) is a theoretical framework on which actions as markers of intent might beneficially be plotted. Similarly Figure 37 (c) illustrates that linguistic and active markers are moderated by the speed of the induced response. Clearly this is highly contextual as the response time will depend on many factors, including the mode of communication, but nonetheless it is purported that intentionality includes a temporal dimension. This assertion emerged from the documentary analysis, which highlighted the effect of the delayed response to the engineer’s emails. The delayed response in this case, wasn’t explicitly, but might beneficially, have been interpreted as a negative marker of intent.

In this case-study a number of linguistic and active markers were retrospectively identified and plotted in Figure 38 as an empirical example of this theoretical construct.

Writing about a company’s commitment to innovation, Slaughter (2000) writes ‘commitment is demonstrated through its internal allocation of resources to the implementation of the innovation’. In this case study the local authority’s allocation of resources to the extraction of additional site-won limestone, was implicitly understood as a demonstration of their intent to implement this technology, were it to prove feasible (see Figure 38 (b)).

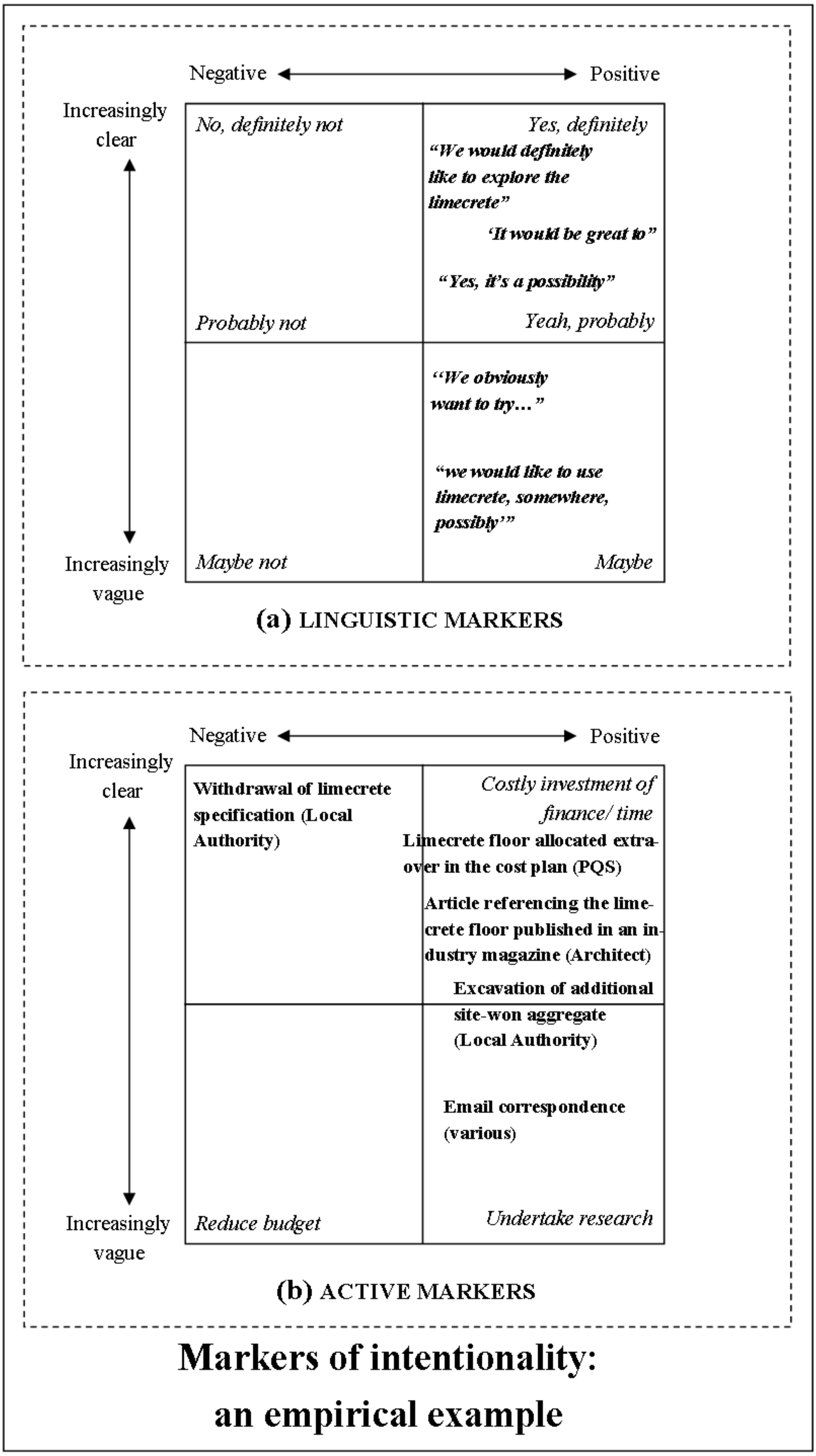

Figure 38: Linguistic and active makers of intentionality from the case study

The other sign of commitment to innovation, highlighted by Slaughter (2000) is, 'public announcement and acknowledgement of (a company's) decision to use the innovation'. When in October 2011 the architect published an article about the new school in Building Design magazine, saying, *'The project employs a simple, earthy palette of materials, including polished limecrete floors, using limestone excavated from the site, as well as rammed earth in places'*, this was interpreted as a demonstration of their intent to implement the novel aspects of the scheme.

18.4.10.1 Implications of language, action and response-time being markers of intentionality in human processes

It is recommended that those managing, or involved in, innovation processes adopt a more conscious awareness of language, action and timing as markers of intentionality. This insight is expected to beneficial not only in interpreting the behaviour of other project stakeholders but also in regulating one's own behaviour so as to avoid ambiguous utterances or actions that might be misinterpreted. The importance of intent in implementation processes, and thus of its effective communication, is discussed further in Theory 11.

18.4.11 Theory 11: Action and intention are mutually constituted

Intentionality has been observed to be essential in both initiating and sustaining innovation processes (see DTM04). More fundamentally intention and action have been observed to be mutually constituted, with one enabling the other in a recursive feedback loop (see Figure 39).

Intentionality is defined as 'the way in which *(our experience)* is directed through its content or meaning toward a certain object in the world' (Smith, 2013). Intentionality is not just an individual phenomenon and 'collective intentionality' is ostensibly more pertinent in the context of engineering design. Collective intention includes 'shared intention, joint attention, shared belief, collective acceptance, and collective emotion' (Schweikard and Schmid, 2013). Specifically, shared intention is argued to 'enable participants to act in a coordinated and cooperative fashion and to achieve collective goals' (Schweikard and Schmid, 2013), which is arguably the essence of the design process. Two constructs, both of which are systems' principles, are highlighted by proponents of collective intentionality. Firstly, that collective intentionality is irreducible, and not simply the sum of individual intentionality and secondly, that human beings are uniquely inclined to cooperate, even when this does not immediately serve each individual's own purposes (Schweikard and Schmid, 2013).

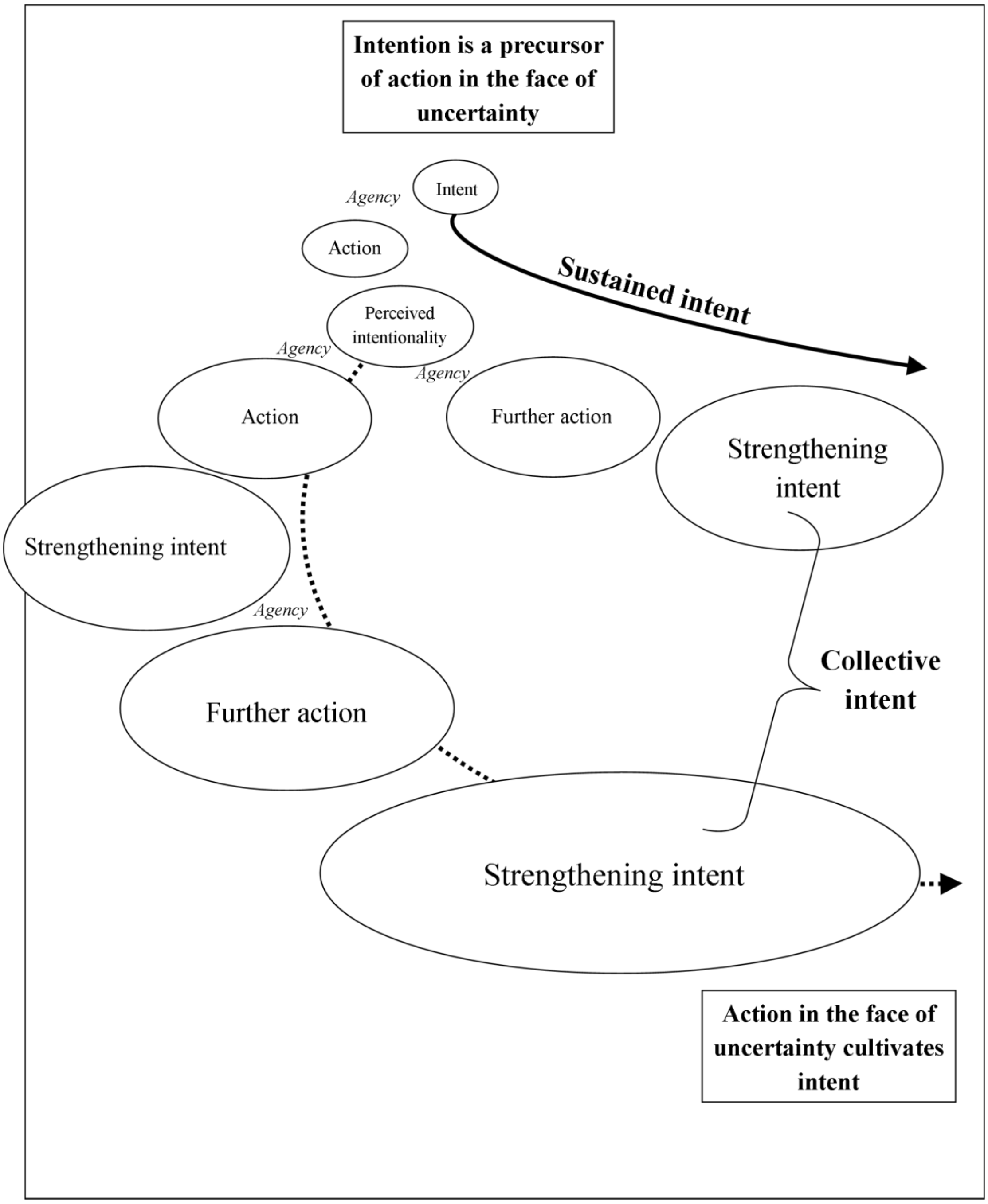

Figure 39: Action and intent are mutually constituted (Theory 11)

18.4.11.1 Implications of action and intention being mutually constituted

The informal and mutually constitutive nature of action and intent, illustrates the emergent nature of collective intent. This theory implies that the action of a single intentional individual can result in a range of actions on the part of a range of individuals. This theory aligns with Granovetter's model of collective acton (Granovetter, 2005). Writing about the active nature of 'Innovation Work' Neumer (2012) writes 'a prior practical test is often more helpful than time-consuming theoretical planning'. It was observed in this study that the 'prior practical test', in this case production of a handful of limecrete cubes containing site-won limestone, did considerably more than just save time, it initiated a chain of actions on the part of a number of individuals, which ultimately concluded in the specification of an innovative lime-pozzolan concrete floor.

A notable disadvantage of the emergent nature of collective intent, is that the initial rasion d'être for desiring an innovative solution is at risk of being forgotten as the design development gets caught up in the nascent intentionality. This may have been true of the rammed earth wall, which was initially conceived as an innovative and ecological solution, but was ultimately built by a contractor who was flown half way around the world to construct it.

18.4.12 Theory 12: Implementation is a mutually constituted process

It has been observed that novel technological artefacts and the systems that adopt them are co-produced (Harty, 2010) or in the words of (Etzkowitz and Leydesdorff, 2000) 'both the innovator(s) and the innovated system(s) are expected to be changed by the innovation'. Take the lime-pozzolan concrete as an example, at the beginning of the case study the school didn't know that 'limecrete' existed, *'we hadn't even heard of limecrete as you know, before you mentioned it to us'* and polished lime-concrete didn't exist, neither as a desired solution or as a technical possibility. By the end of the process, not only had the technology itself been changed but also so had the actors *'we have had to lose some of our passions - such as the limecrete'*. The co-production of social and technical systems, that makes the implementation process worth managing for the sake of those involved in it, as well as just being a means to an end. For example, in this case study an unintended consequence of the applied-innovation process was to increase the 'learned helplessness' (Seligman, 1998) of at least one of the stakeholders.

18.4.12.1 Helplessness versus resilience

One observation from the interview data was the asymmetry of individuals' responses to the omission of the lime-concrete. Both SLT(A) and ARCH(B) used a similar metaphor in describing how this event made them feel, but the degree to which they were impacted is observed to be quite different.

[SLT(A)]: *'so then I felt equally crushed when it felt like the limecrete wasn't going to go anywhere in our own small project.'* (lines 20-21)

[ARCH(B)]: *Just a feeling of slight deflation, I think for me//*[ARCH(A)]: *Yeah there is a slight deflation. But don't think it has put us off trying things with materials.*[ARCH(B)]: *No.*

Further amplifying the asymmetry the main contractor was barely implicated by the decision, in fact it is observed to have made his life easier (line 267).

[M.CON(A)]: *Okay so whereas I had an item on my activity schedule for grading as-dug material, I just on T2 I took that out. Just deleted it. (176-177).*

[M.CON(A)]: *but we just literally trying to get our head round it, and it was taken out. So really that was that, (.) (249-250).*

[M.CON(A)]: *So it was like (...) so for tender it was easier. (line 267)*

Seligman (1998) has studied the asymmetry in individuals' rate of recovery from bad events, commenting *'Failure makes everyone momentarily helpless. It is like a punch in the stomach. It hurts but the pain goes away-for some almost instantly. For others the hurt lasts'.*

Reflecting on this phenomenon Seligman (1998) has suggested that time it takes for 'the pain to go away' is dependent on an individual's world-view, which is evidenced in their 'explanatory style'. Specifically, a personalised, permanent and pervasive interpretation of bad events is argued to lead to long-lasting helplessness, whereas an external, temporary and specific interpretation produces resilience (Seligman, 1998).

The interview with SLT(B) was conducted eight weeks after the decision to omit the lime-concrete floor, but her portrayal of the situation implies that she is still affected. The innovation process is observed to have had a pronounced and long-lasting impact on SLT(B), which Seligman (1998) would argue was the result of her 'explanatory style'.

The following instances from provide evidence of what Seligman (1998) describes as a 'personalised explanatory style'

SLT(B): '*you know, here I am – as mature and experienced as I'm ever going to get in this job and I've still got somebody saying to me, no you can't do that, you can't make that decision, and it's a real frustration, it's a powerful frustration'* (lines 73-75).

Interviewer: *Do you think that that has an effect on you as a person, or does that ...*

SLT(B): (cutting in) *'yeah definitely! It makes me massively frustrated with my job' (lines 91 and 92).*

SLT(B): '*... yeah, it's so, it was a feeling of personal failure for me as much as anything else' (line 157).*

Similarly, the utterance in lines 83-85 provides evidence of a 'pervasive and 'permanent' explanatory style:

SLT(B): *'because with local authority people it is always always things grind immensely slowly, things are predicated on safety, on precedent, on minimising risk' (lines 83-85)*

Writing about barriers to change in organizations, Senge (2006) comments that a 'more daunting form of resistance is cynicism' In the face of uncertainty cynicism rapidly closes down unpredictable future perspectives and courses of action. On the other hand, personal optimism endures uncertainty, holding all potential courses of action in the balance.

The main thrust of Seligman (1998)'s work is that 'helplessness' or 'optimism' is not a character trait, but rather learnt from an individual's explanation of their circumstances. In this project 'learned helplessness', on the part of SLT(B), is thought to be an unintended consequence of the non-adoption of the novel lime-concrete floor.

[SLT(B)]: *'And part of me was actually was that every time you do embrace a change you have to be prepared I think to..to be disappointed really, and you know to compromise and that is every single thing we do'* (lines 60-62).

In this specific case SLT(B) use of 'part of me' at the start of this reflection is thought to be pertinent, for she was went on to reflect further on this theme herself, commenting:

[SLT(B)]: *'but it was really frustrating – however, you know you have to have enormous amounts of resilience, working as you do, in that kind of area, as I do too* *as a leader, but I notice it with [ARCH(A)] as well, every time I speak to him about something, he kind of has this capacity to bounce back, which I don't know whether is to do with his youthfulness or to do with the fact he is just used to working in this – as an architect in this industry – but it seems to be that that must be part of what you have to be able to have, <u>just an immense capacity for resilience and determination</u> and sheer bloody mindedness actually, that in the end you will get want you want'* (lines 114-121).

18.4.12.2 Implications of implementation being a mutually constitutive process

It is clear from this analysis that the outcome of an innovation process, whether positive or negative, has an impact on the people involved in it. Resilience, which sustains optimism in the face of negative outcomes, is recognised to be a key determinate of an on-going willingness to innovate. In the light of this insight, managers should be mindful of the impact that efforts to effect change in the environment has on participants themselves and endeavour to mitigate injurious learning, which has been observed can be an unintended consequence of the applied-innovation process. Specifically, to mitigate the risk of propagating 'learned helplessness' Seligman (1998) promotes the identification of 'specific, temporary and external' causes of failure.

19 Reflection on the outcome of the case-study story

The aim of analysing the case study project was to gain a deeper insight into how innovative and sustainable construction materials are evaluated, integrated and ultimately specified in construction design projects. This section briefly reflects on the outcome of the design process in the case of this project, with respect to the implementation of innovative and sustainable material technologies.

A number of potential technologies were presented to the design team at the outset of the project. Three materials were subsequently embedded into the design: CLT, rammed earth and lime-pozzolan concrete. Each material's story is briefly summarised below.

19.1.1 Cross-laminated timber

Cross-laminated timber (CLT) was seen to be embedded in the architects' vision of the scheme from the earliest stage of the project (see the discussion of DTM01). Although a steel frame was also schemed at Stage C as a point of comparison for the client, the form and aesthetic of the building was so contingent upon the modularity and structural characteristics of the timber panels, that this was thought to be little more than a precursory exercise.

Design consistency coupled with the growing acceptance of CLT in the UK market, the client's previous positive experience of CLT, the experience and professionalism of the tendering CLT sub-contractors, the anticipated programme benefits and the proximity of the architect and chosen sub-contractors offices, meant that the implementation of this innovative technological solution was largely straightforward. The CLT superstructure was erected in January 2013 (see Figure 40).

Figure 40: Erection of the CLT frame, January 2013

19.1.2 Lime-pozzolan concrete

The design team, including the school were interested in this novel technology from the outset of the project. When it was shown in the laboratory that site-won limestone could be used as aggregate, a bespoke lime-pozzolan concrete was pursued. A number of applications were considered during the design process, including the spine wall, foundations, retaining wall, ground floor slab and finished floor surface. A non-structural application was pursued as a low risk application of this novel concrete technology; specifically a polished lime-pozzolan concrete floor screed was specified as part of the tender documentation at RIBA Stage D (see Figure 41).

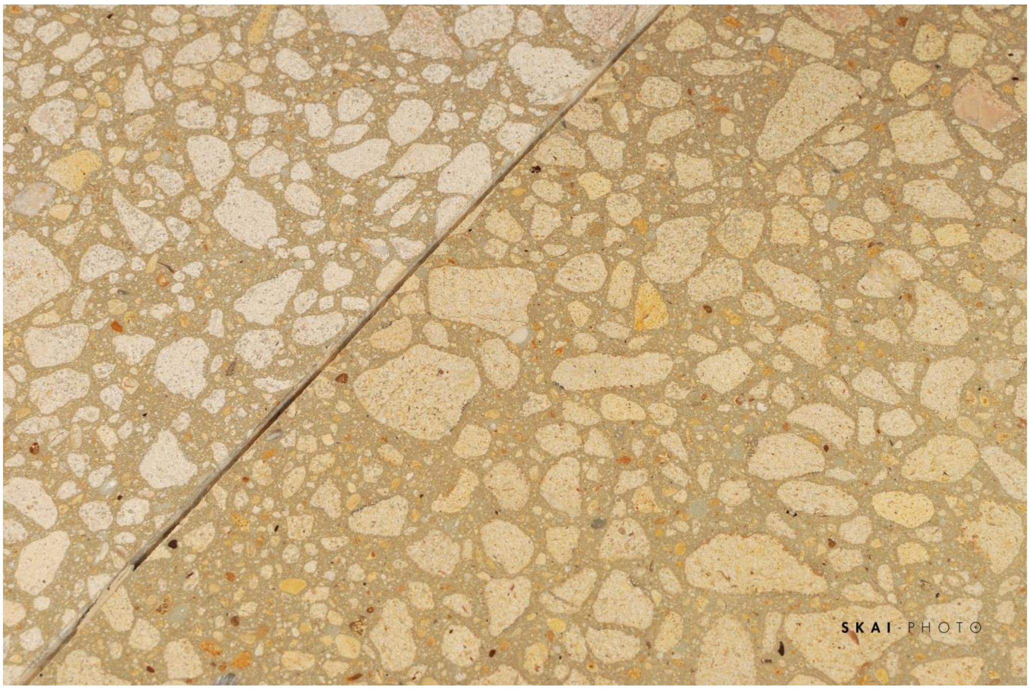

Figure 41: Polished lime-pozzolan concrete with oolitic limestone aggregate

A week, or so, after the lime-concrete specification was issued the local authority client requested its withdrawal; they were not prepared to specify the innovative polished lime-concrete floor unless they could see it demonstrated in another school. Further testing was recognised as being necessary to verify the performance of the polished lime-pozzolan concrete floor in use. Specifically the slip, chemical and wear resistance of the polished surface were untested at the time at which the decision had to be taken. It was suggested that these aspects of the floor's performance would primarily be determined by the coating applied during the polishing process, but further testing was needed to substantiate this conjecture. Further substantiation of the design was prevented by the project programme, or more accurately by the procurement route, as in reality the floor of the building was not laid for a further sixteen months.

Rather, a proprietary dry-shake polished concrete floor was specified and laid in the hub space and linoleum in the classroom areas. Figure 42 shows the finished floors.

Figure 42: Finished floors in the new school extension

19.1.3 Rammed Earth

When site-won earth was shown to be suitable for construction of a rammed earth wall, load-bearing rammed earth was considered for the spine wall. To minimise the impact of the rammed earth wall on the construction sequence and to reduce the total cost, a smaller non-load bearing application was pursued.

Although the implementation of novel technologies has been differentiated from the adoption of novel technologies, the story of the rammed earth wall speaks about the efficacy of the adoption decision in this case study. Once the decision to incorporate a rammed earth wall in the scheme had been made, the client went to considerable lengths to realise this novel aspect of the scheme. When no UK sub-contractor was available, or prepared, to construct the cement-stabilised rammed earth wall, a sub-contractor was flown from Australia to build this aspect of the scheme (see Figure 43).

Figure 43: Rammed earth partition wall

The CLT and the rammed earth are seen from Figure 40 & Figure 43 to have been implemented but the lime-pozzolan concrete was substituted for a proprietary polished concrete solution.

20 Conclusions

This qualitative research project has deconstructed a real-world construction project with the view to extracting ‘an emergent understanding of a culture’ Lloyd (2000). Specifically, this process-tracing case study (George and Bennett, 2005) was used as a vehicle for investigating the implementation of innovative and sustainable materials in the construction industry. Going back to March's (1991) model of organisational learning, *implementation* is purported to be the value-realizing, technology-translating, socially-transforming step between exploration and exploitation.

In depth scrutiny of a ‘real-world’ case study project, seeking to implement lime-pozzolan concrete, has shown that the implementation process, once initiated, is an experiential, social, contextual, active, interactive, temporal, intentional and mutually-constituted process.

The following theories look back at the case-study story with a view to summarising what emerged from the analysis.

20.1 Theory 1: Implementation is a phenomenological process

- It has been observed that the phenomenological, or conscious, experience of human actors in the implementation system is influential in motivating, steering and sustaining action. Positive experiences, whether belonging to the past, present or the imagined future, are enablers of innovation; correspondingly negative experiences inhibit innovation.
- Interest and existentialism have been identified of enablers of applied-innovation, a process which nurtures humankind’s innate curiosity and desire to change to world.
- The primacy of conscious experience coupled with humankind’s reflective nature results is a high degree of individual interest in the process, which is evaluated separately from the outcome in design.
- Insights illuminating the fundamental nature of human experience and endeavour support the theory that innovation is a mutually constitutive process, which effects change in both the environment and in the participants.

- The phenomenological nature of implementation supports the theory that experience, rather than imagination, is the source of the innovator's instinct (Böhle et al, 2012a).

20.2 Theory 2: Implementation processes are guided by individual heuristics

- Individual cognition has been observed to be a powerful mediator of human decision making and action in applied-innovation processes.
- Physical samples were observed to encourage 'cognitive prospection' (Buckner and Carroll, 2007), helping individuals to create richer mental simulations of the final building. Physical samples also facilitated sensory evaluation, which was observed to stimulate an 'affective' mode of thought.
- Novel artefacts were observed to result in disparate meanings and mental-models, which were more or less conducive to implementation.
- Self-efficacy beliefs, such as creative confidence (Plattner et al., 2012), were observed to be beneficial in facilitating action in the face of uncertainty and thus recognised to be an enabler of implementation processes.
- The degree of novelty of an innovative solution was seen to be highly asymmetric due to its subjective and relative nature. The observation that the degree of novelty of an innovation is evocative in stimulating positive or negative affective beliefs implies that the degree of novelty has to be carefully communicated and rigorously considered in context.
- Given that it was recognised that collective action calls for compatible meaning, it is argued that the social process through which meaning is negotiated and stabilized, might be beneficially structured to promote convergence.

20.3 Theory 3: Implementation processes are guided by 'affective' decision-making

- The incidence of 'affect' in the empirical data has highlighted the influence of 'affective' judgements and decision making in applied-innovation processes.
- Features of the applied-innovation process evoking affective, or emotive, responses are asserted to be highly influential in effecting individual risk perception and thresholds and thus in steering the outcome.

- As a positive affective belief, visual attractiveness of the material samples is thought to have downplayed the perceived risk of implementing this novel technology.
- The importance of ‘observability’ in innovation implied that the value of applied-innovation is at least in part secured the long-term readability of the artefact. Given the observed relationship between narratives and human affective experience, it is recognised to be beneficial if the innovation-story is inherently readable in the artefact such that it can inspire creativity in others.
- Haptic perception is asserted to be an influential and experiential device in the evaluation and specification of building materials.
- Risk was recognised to be an inherent feature of innovation and a largely subjective phenomenon. Perceived risk is a dynamic and experiential phenomenon influenced by affective beliefs.
- Action does not require perceived risk to be entirely eliminated just reduced below an indeterminate and moveable threshold.
- Contextual phenomena are determinants of risk tolerance. For example the profile of the project was seen to amplify the perceived risks and benefits and thus influence willingness to innovate.
- Affective decision-making was thought to be beneficial in the early stages of innovation processes, because it helped individuals ‘suspend disbelief’ (Colleridge in Schaper, 1978), facilitating an open attitude and accommodating a high degree of uncertainty. Devices that stimulate and heighten positive affective beliefs, such as material samples, innovation storyboards and anecdotal experiences are thus argued to have been valuable at the project outset.
- Implementation requires a timely transition from ‘risk as feelings’ to ‘risk as analysis’, in order for formal risk management procedures to be effectual in mitigating and assigning risks.

20.4 Theory 4: Implementation is a social process

- This study provided evidence that group dynamics have a significant effect on the perception of risk (social contagion).

- Strong relationships, encouraged by frequent and empathetic communication between members of the design team, increase the level of respect for other's evaluation of the innovation.
- Like affective decision-making, social contagion is beneficial at the outset of the implementation process as it allows a higher overall level of uncertainty to be tolerated, buying valuable time for seeking out the information that will be effective in reducing it.
- Conversely social contagion was also seen to have latterly become detrimental to the applied-innovation process masking the requirement for a formal risk management procedure.
- Competitive tendering hinders innovation by precluding 'interessement', the pro-active social process of mobilising interests and creating alliances to support innovation (Akrich et al., 2002), during the initial design development process.
- Interessement was observed to be the primary activity of the main contractor at the first tender stage.
- The interessement process reveals resisters and assistors to innovation. An excess of resistors and/or a lack of assistors is a significant threat to implementation as a social process.
- Design and Build (D&B) procurement does not allow for design as a social process. The transfer of the design from the client led design-team to the main contractor interrupts the social process, changing the relationships between the client, the design team and the design.
- Competitive tendering undermines emergent properties of the design process such as social capital and collective intentionality, hindering applied-innovation.

20.5 Theory 5: Implementation processes are contextually embedded

- The ability to identify the contextual features of a project that typically support or supress innovation would be valuable in preventing wasted time and effort.
- In the case of the implementation of novel materials, when long-term performance engenders a higher degree of uncertainty than mainstream solutions, contractual liabilities need to be expressly understood.

- The procurement route can impose artificial programme constraints on the project, detrimentally constricting the concurrent innovation process.

20.6 Theory 6: Implementation processes are initiated

- Technology coupling is a two-stage process. Firstly, an inspiration or identification conceptual hook. Secondly, a more or less subconscious alignment check during which stakeholder's broader purpose is brought to bear on the innovation.
- Representation, the propensity of humans to create and assign meaning through symbolism, is an emergent property of the technology coupling process at the initiation of applied-innovation.
- Through representation innovative artefacts are attributed meanings beyond themselves. Though symbolic-meanings can be an enabler of innovation processes, representation heightens disappointment in the event of implementation processes being unsuccessful.
- Alignment of individual values or interests with applied-innovation is asserted to be effective in initiating and sustaining innovation processes. The impetus that has been observed to emanate from this alignment is a compelling argument for not compartmentalising professional work from other values and interests.

20.7 Theory 7: Implementation is predicated on human action

- The active nature of implementation demands efforts to create and maintain the conditions necessary for individual action. Specifically, the means, motive and opportunity to act.
- The active nature of implementation calls for a greater consciousness and emphasis on human agency in design.

20.8 Theory 8: Implementation is an interactive process

- Language is used to propel and steer implementation processes in design. For example, 'black hat' utterances have been seen to be effective in driving the design process forward by closing down surfeit options and thus helping participants converge on a solution (see DTM03).

- Language has been observed to be used to talk-in and talk-out aspects of the design.
- Language is powerful in dispelling or aggravating uncertainty in design processes.
- Language provides insights into heuristic decision-making processes in design and can be effectively used to interrogate otherwise subconscious cognitive processes.

20.9 Theory 9: Implementation is a temporal process of human activity

- In this case the applied-innovation process was undertaken in parallel with the main project process. The 'temporal pacing' of the two concurrent processes was observed to be mutually constituted.
- The implementation process in this case study was seen to be susceptible to temporal effects such as interruptions, lags, lulls and holdups.
- In the context of human activity systems, innovation is vulnerable to human limitations including the lack of, or diminishing, attention or impetus, which can disrupt or impede temporal initiatives.

20.10 Theory 10: Language, action and response-time are markers of intentionality in human processes

- 'Intentionality markers' are continuously and intuitively interpreted as indicators of others intent.
- Positive and clearly defined design-intent is an enabler of innovation justifying further action. Correspondingly, a lack of clarity about design-intent was observed to inhibit further design-development.
- Action is purported to be a clearer marker of intent than language, although it was recognised that actions, like language, can be more or less vague.
- Intentionality includes a temporal dimension; with others response-time indicative of their intentionality.
- A conscious awareness of language, action and timing as markers of intentionality is thought to be valuable in interpreting and guiding behaviour in applied-innovation processes.

20.11 Theory 11: Action and intention are mutually constituted

- Implementation processes are contingent on sustained intentionality.
- Intention and action have been observed to be mutually constituted, with one enabling the other in a recursive feedback loop. Intention is a precursor of action in the face of uncertainty and action in the face of uncertainty cultivates intent.
- Collective intent is argued to be an emergent property of the informal and mutually constitutive system of action and intent.
- On the strength of this theory, large scale initiatives might result from the action of a single intentional individual.

20.12 Theory 12: Implementation is a mutually constituted process

- By the end of the process, not only had the technology itself been changed but also so had the individuals who had participated.
- ‘Learned helplessness’ (Seligman, 1998) was identified as a potential unintended consequence of unsuccessful efforts to implement innovative solutions.
- Resilience, which sustains optimism in the face of negative outcomes, is recognised to be a key determinant of an on-going willingness to innovate.

20.13 Implementation as a human centric systems

The most apparent, and arguably most compelling, feature of the research findings is the prominence of human actors in the emergent theories. Collectively the aforementioned findings ‘bring the enactive person to the forefront’ (Bauer, 2012).

In the early 1980’s recognition of the central role of human actors in system performance, highlighted the limitations of traditional systems engineering (SE) approaches and resulted in the development of the soft-systems movement (Mingers & White, 2010). The emergence and on-going interest in soft-systems approaches, both in academia (Mingers & White, 2010) and in the engineering community (Royal Academy of Engineering, 2007), validates the primacy of human actors as the overarching conclusion of this research.

Surfacing some of the intricacies of applied-innovation processes evidently does little to reduce their complexity; rather it may appear to do quite the opposite. In reality, complexity, as an inherent property of the system and is fundamentally unchanged by academic insight.

The process of surfacing underlying phenomena is the core activity of soft-systems methodologies and problem structuring methods (PSMs), which ultimately aim to 'alleviate complex, problematic situations' (Mingers & White, 2010). The value of interactive planning (Ackoff, 1993), strategic assumption surfacing and testing (Mitroff & Mason, 1981) and soft-systems methodology (Checkland, 1999) lies in their efficacy. Participatory approaches surfacing-complexity have been observed to be efficacious in finding solutions to otherwise intractable or 'messy problems' (Schon, 1995) The use of such 'complexity-surfacing' tools in a management capacity is not only recognised to be effective but also acknowledged to be more ethical than the subliminal nudging and priming techniques that behavioural economists, such as Ariely (2008), have identified as being used to manipulate human behaviour.

The intricacies and idiosyncrasies of human behaviour are not thought to be problematic in and of themselves, quite the opposite for this complexity is also the source of humankinds unique creativity and beauty. Manmade systems, be they physical or organisational, which fail to recognise or to take into account mankind's unique complexity and creativity not only result in deleterious outcomes, but also bring about or highlight, mankind's subversive nature, depending on your world-view.

The other crucial observation from this study is that although human activity systems are complex, that the applied-innovation is predicated on what Boden (1996), describes as 'our ordinary abilities', which she lists as 'noticing, remembering, seeing, speaking, hearing, understanding language and recognising analogies'. Furthermore, the observed parallel between the emergent results and Boden's work on creativity suggests that implementation is in essence a creative process.

The purpose of this research was to gain a more holistic understanding of the implementation process, in order to improve the management of applied-innovation processes in construction. Govindarajan and Trimble (2010) have suggested, 'The limits of innovation in large organizations have nothing to do with creativity and nothing to do with technology. They have everything to do with management capability'. Furthermore, it is recognised that the intra-organisational project-based nature of innovation in construction acts to amplify the management challenge.

Identifying specific management tools and techniques was beyond the scope of the research, but this study does offer project-managers a breath of theoretical insights against which current practice in construction can be evaluated and upon which new tools might be developed to support innovation in construction.

Nicholas and Steyn (2012) recognise four evolving views on management: the classical viewpoint 'which establishes principals for planning, organising, leading and controlling', the behavioural viewpoint, which considers 'the human and social aspects of organizations' and the systems viewpoint that 'looks for ways to understand the elements and dynamics of a situation' and finally, 'the contingency viewpoint', which suggests that managers must be adaptable and able to apply all three of these views independently, or in combination, depending on the situation.

Reflecting on each management view in turn, it is clear that the classical view of management is valuable in planning, organising and controlling the temporal and active dimensions of implementation. The behavioural management view is fitting with phenomenological and intentional nature of implementation processes and the systems view is consistent with its contextual, social and interactional nature.

It is acknowledged that construction projects rarely, if ever, have a designated innovation-manager and that that management role is normally taken on by a member of the project-team. The term 'innovation-manager' in this instances has been defined as 'the one who gets all the others involved and then organizes and directs their efforts so everything will come out right' (Nicholas and Steyn, 2012). In this scenario a managerial approach is arguably more valuable than the description of a unique role.

20.14 Managerial approach

The phenomenological, or experiential, nature of applied-innovation processes makes a case for planning and managing the design process itself, with the express intention of guiding or enhancing the experience for the design team as participants in the process. This is a radical shift in managerial attention from the outcome of the process to the process itself. Many professional occupations are founded on designing, creating and enhancing human experience; with retail, hospitality and entertainment providing obvious examples of the delivery of human experience. Although human experience is a key concern of architects, an experience-centred approach to design is thought to be less explicit in the construction industry. Furthermore, experience-centred design is thought to be almost exclusively geared towards the end user rather than participants in the process.

On the strength of the empirical evidence provided by this case study, management of the implementation process is argued require the creation, and navigation between, four discrete phases, or levels, of design activity.

The first phase should promote an open attitude to innovation and accommodate uncertainty. The second phase should be concerned with the timely transition from an 'affective' to an analytical assessment. The third phase should be concerned with enacting formal risk procedures and contractual arrangements. The final phase should be reflective and recognise project learning and achievements. The nature and key features of each of these discreet phases is outlined in Table 35.

Table 35: Innovation management framework

NATURE OF PHASE 1	NATURE OF PHASE 2	NATURE OF PHASE 3	NATURE OF PHASE 4
Creative Open Affective Experiential Active	Transitional Social Judicious Wise Active	Analytical 'Serious' Active	Evaluative Reflective Active
FEATURES OF PHASE 1	**FEATURES OF PHASE 2**	**FEATURES OF PHASE 3**	**FEATURES OF PHASE 4**
Yellow, red and green hat thinking Inspirational Fun Existential Anecdotal Experimentation Heuristic Hands-on experience Technology story boarding Meeting of minds Mental models Suspense of disbelief Play	Information seeking Interessement Black hat thinking Risk identification Convergence Intent Validation	Risk management Contractual arrangements Logistics Project-management	Learning Explaining Communicating lessons Exemplification Celebrating

The language, the temporal-pacing and the boundaries of design in construction may well be transformed in the near future, but the human elements: design philosophy, representation, perceptions, creative confidence, resilience, existentialism and the experiential nature of design and implementation processes will persist.

21 Limitations of the research

A key limitation of theory-building from case-study research is the inevitable emergence of untested theories. It is recognised that the theoretical conclusions are grounded a single case study and that further research is necessary to substantiate their generalizability across multiple case studies or individual projects. It might be valuable for such research to be undertaken by a social scientist rather than an engineer, whose education would render him/her more attuned to the individual and collective behavioural phenomena that have been observed to prevail in this case study.

Classical, behavioural and systems management approaches all rely on tools and procedures for organising, supervising, understanding, motivating and directing human effort. This research has not endeavoured to identify or design specific tools that might on the strength of this research usefully be developed to assist with implementation processes in practice.

22 Further work

One area of further research that is considered to be of particular interest is the impact of developments in Information and Communication Technologies (ICT) on innovation processes in construction. Specifically, how will evolving design practices facilitated by advances in ICT effect innovation in the construction industry?

New Information and Communication Technologies (ICT's) have radically transformed, and will continue to transform the environment in which humans operate and communicate. Yet the design process in construction, is largely untouched by any of the new features offered by recent developments in ICT and social media, certainly not within the researchers experience during this programme. Many of the tools that are available, and increasingly familiar in everyday communication, respond directly to the different conceptualisations of implementation identified in this research. These tools are therefore thought to have the potential to impact the way construction professionals work. For example instant messaging and Twitter have the potential to transform temporal and interactive decision-making processes, Facebook and LinkedIn to transform social processes including 'interessement' and Pinterest to transform technology 'coupling', mental models and cognitive prospection in design. Reflecting on the role that social media can play in Business Process Management (BPM), Pearson (2013) comments, 'Fortunately, social media offers us a chance to improve the communications supporting process improvement'.

One new process innovation that is currently being implemented in the construction industry is Building Information Modelling (BIM). BIM employs 'computer generated n-dimensional models to simulate the planning, design, construction and operation of a facility' (Azhar et al., 2008). Although studies have explored the risks and benefits of the adoption of BIM in construction, there appears to be little consideration of the effect that these 'data-rich, object-oriented, intelligent and parametric digital representations' (Azhar et al., 2008) will have on the design process from a phenomenological perspective. In time BIM may well provide a new platform for radically different ways of communicating and managing design processes including applied-innovation.

23 Overall conclusions

This research has used a novel construction material (lime-pozzolan concrete), a real-word project (a school) and the lived-experience of a number of construction professionals, as a vehicle for investigating the *implementation* of innovative and sustainable materials in construction.

Implementation has been defined as *the process by which science translates into socioeconomic progress*, or in short *-applied-innovation.* In this thesis *implementation* is argued to be the value-realizing, technology-translating, socially-transforming step between exploration and exploitation. Specifically, the implementation of new technologies at a project-level is recognised to be an antecedent of technological change in the construction industry. Furthermore, technological change is held to be an antecedent of sustainability.

In the dialogue about the transition to new sustainable technologies, the emphasis on 'implementation' put human action right at the centre of the sustainability story. Specifically, this thesis has focused on managing the transition to a more sustainable built environment from a socio-technical perspective. The methodological approach was to follow the story of an innovative and sustainable construction material, lime-pozzolan concrete in the 'real-world'.

23.1 Part 1: Exploration

Laboratory research followed an 'engineering-design' approach, seeking to substantiate the feasibility of structural strength, low-CO_2, concretes based on hydraulic lime.

This project was successful in demonstrating the feasibility of producing modern, hydraulic lime-pozzolan concretes with comparable strengths to Portland cement based concretes, demonstrating that lime-based concretes can attain 28-day compressive strengths of up to 50MPa, which is thought to be a step-change for lime-based construction materials. The results of this research clearly illustrated the efficacy of water reducing admixtures and reactive pozzolanic additions (and combinations thereof) in substantially increasing the mechanical strength of hydraulic lime-based binders. Mechanical strengths comparable with those obtained in Portland-cement based concretes, were recognised to increase the range of potential applications of hydraulic lime in construction, although the relationship between strength and other performance benefits, such as breathability, were recognised to be of great importance in future work.

This study also provided empirical evidence that a hydraulic lime-pozzolan concrete, containing a high proportion of aluminiosilicate minerals, had an embodied CO_2 around 64% lower than a CEMI, and 41% lower than a CEMIII/A, concrete of equivalent strength. Moreover, the potential for lime-pozzolan concretes with a lower still CO_2 and energy intensity was noted.

It is acknowledged that the environmental credentials of lime-pozzolan binders was not understood in comparison to those of alternative future binder technologies that are also being developed and that further work is needed to appraise the value of these findings in the context of the search for low-CO_2 cementitious binders.

Three project-specific lime-pozzolan concretes were developed during this research programme in response to project-specific requirements. This project-led approach is thought to have resulted in identification of three satisficing (and thus probably sub-optimal) solutions as opposed to gaining a broader knowledge of the solution space in which a range of optimal solutions for different projects might lie.

A strategic market analysis was used to highlight a range of potential applications for this innovative concrete technology, with the future development of lime-pozzolan concretes discussed at some length in the context of four primary market sectors: low impact buildings, conservation of historic structures, appropriate technology and composite structural systems.

The primary limitation of this research is that no specific testing was undertaken to understand the reaction chemistry and thus to explain the observed mechanical performance of lime-pozzolan binders at a macro-scale. An understanding of the reaction kinetics, is recognised as being valuable in the selection of suitable constituents, the optimisation of the binder, the identification of possible degradation mechanisms as well as in informing best practise in the use of lime-pozzolan binders in construction.

23.2 Part 2: Implementation

The purpose of this research was to gain a more holistic understanding of the implementation process, in order to improve the management of applied-innovation processes in construction. Industry-based practitioner research, focused on project-level communication has provided empirical evidence of the socio-technical complexity of applied-innovation.

Section 2 of the thesis comprised rigorous analysis of a case study construction project, with the aim of identifying opportunities to improve project-level design processes in order to support the uptake of innovation and sustainable solutions. Twelve high-level theories about the nature of implementation processes were built upon twenty-five constructs emerging from the case study analysis, namely:

Theory 1: Implementation is a phenomenological process

Theory 2: Implementation processes are guided by individual heuristics

Theory 3: Implementation processes are guided by 'affective' decision-making

Theory 4: Implementation is a social process

Theory 5: Implementation processes are contextually embedded

Theory 6: Implementation processes are initiated

Theory 7: Implementation is predicated on human action

Theory 8: Implementation is an interactive process

Theory 9: Implementation is a temporal process of human activity

Theory 10: Language, action and response-time are markers of intentionality in human processes

Theory 11: Action and intention are mutually constituted

Theory 12: Implementation is a mutually constituted process

Collectively, these theories demonstrated that implementation is a human, value-laden process, shaped by the interests, beliefs and actions of a collection of idiosyncratic actors. The implications of each individual theory in turn were also discussed.

Surfacing some of the intricacies of applied-innovation processes, specifically recognition of their experiential, social, contextual, active, interactive, temporal, intentional and mutually constituted nature, did little to reduce their complexity; indeed on first reflection it appeared to have done quite the opposite. However, in the light of the efficacy of problem structuring methodologies (PSM's) in soft-systems practice (Mingers & White, 2010), this thesis suggested that problems are not 'messy' or 'wicked' as a result of the inherent complexity of human consciousness per se, but as a result of manmade systems and processes, that wilfully, or subconsciously, overlook, or discount, this complexity. Moreover, the findings of this research suggested that the complexity embedded in what Boden (1996) described as 'our ordinary abilities' (noticing, remembering, seeing, speaking, hearing, understanding language and recognising analogies) was the source of human creativity, implied that implementation was in essence a creative process.

The phenomenological, or experiential, nature of applied-innovation processes made the case for planning and managing design processes, with the express intention of guiding or enhancing the experience for participants. In the light of the active nature of implementation processes, human engagement was recognised to be critical in bringing about technological change. This thesis argued that processes and systems need to be expressly designed and managed to create and enhance positive experience, which was thought to be the key to human engagement. Given that engagement entails 'confronting the world in a manner open to experience' (Bauer, 2012), the relationship between positive experience and engagement is almost certainly mutually constitutive. On the flip slide negative experience is recognised to be disengaging and a lack of resilience is thought to lead to disenfranchised individuals or social groups, which inhibits change.

On the strength of the empirical evidence provided by this case study, management of the implementation process was argued require the creation, and navigation between, four discrete phases, or levels, of design activity. The purpose and defining features of these four phases were initially unpacked but not developed into specific tools.

The empirical findings of this research both call for and enable a greater understanding of behavioural and social science in engineering design and design management. This was an overarching conclusion that was both facilitated and validated by an interpretive soft-systems research approach.

23.3 Reflections on the nature of practice in industry and academia

This industry-based research, spanned the boundaries of academia and industry, and thus facilitated research at the interface of research and design in practice.

Both research and design were observed to be complex human activities, in which judgements were made based on human inference and decisions-reached and enacted based on perceptions of past, present and future realities.

Design particularly, is commonly undertaken by numerous disparate individuals acting independently in real time. Discrete decisions, and the decision making actors that produce them, are not only separated by time and space, but also by their unique experiences of the past, through which their unique expectations of the future are mediated. As a result of these differing experiences, and resulting expectations, individuals attribute different meanings and values to the systems they are creating. These factors in turn inform their perceptions, their behaviours, their aspirations and their decisions. To add to the complexity, these aspects of decision making are typically both unconscious and implicit. Given this, it is quite remarkable that the products, services, infrastructures and systems, with which we are familiar, ever get designed and implemented (Dubois & Gadde, 2002). Yet, design activity as a process, with the expectation of a collective outcome and shared benefits, facilitates a disparate group of individuals to take decisions which culminate in the implementation of a coherent and realisable end product.

Knowledge is also a system of human creation. Although pure research, aspires to objectivity, it too is inherently subjective as it is also contingent upon human decision making and action. At any given time the research agenda is a unique product of collective interest and perceived benefits. Just as in the case of design, the meanings and values that academics attribute to their research, is typically both unconscious and implicit.

23.4 Drawing the two tranches of the research together

The two tranches of the research although wide-ranging are very much interrelated for the research reported in this thesis has a single narrative thread. The story of the lime-pozzolan concrete in the real world, as described in Section 2 of this thesis, only came about as a result of interest in the laboratory research, described in Section 1, the direction of which was influenced by questions emerging from the project and so forth.

Another common thread is the experience of the researcher and the learning that can be attributed to active participation in the research process. On reflection, this observation is in itself attributable to the leaning acquired during the research process, but such is the nature of conscious experience.

23.5 Evaluation of the research approach

This industry-based academic research programme is held to be an example of Collaborative Practice Research (CPR) (Mathiassen, 2002). In line with the core objectives of CPR, which focuses on 'improving the way in which we do research' (Mathiassen, 2002), this EngD research project is itself a case study and this section concludes with a reflective evaluation of the effectiveness of this approach in the development of an innovative construction material.

The explicit and upfront objective of a 'real-world' solution fostered an 'engineering design' approach to this materials research programme. Reflecting critically on this research experience as a whole, a number of advantages and disadvantages of this approach have been identified:

23.5.1 Advantages

- The 'real-world' project that inspired and steered the research programme, was evidence of 'industry-pull' verifying the relevance of the research work.
- The demands of a 'real-world' project programme, necessitated results in a short period of time. In less than two years 'structural lime-concrete' went from being a conceptual idea to a tangible reality. That said, the laboratory testing of this new concrete technology is highly unlikely to have been able to have kept pace with the project programme, had it not been substantially extended by the protracted planning process.
- This approach was held to be good at realising 'correspondence', which Katsikopoulos (2009) defined as 'success in the real world'. A structural substantiation report, based on the results of this laboratory testing (as well as a lime-pozzolan concrete cube in the hands of the building control officer), were satisfactory in attaining unqualified Building Control approval for an

innovative structural lime-pozzolan concrete shell roof. Clearly the successful construction of the shell roof would have been the ultimate demonstration of research correspondence in this case.

- The engineering-design approach both required and facilitated a great deal of agility in the research programme. The testing was not only steered by the external project but responded to concurrent ‘real-world’ events. For example the winter weather conditions both prompted and facilitated testing looking at the effect of cold-weather curing on the strength development of lime-pozzolan concretes.
- A strategic marketing approach was effective in identifying areas of future work for development of this technology.

23.5.2 Disadvantages

- The scope of the research is thought to have been sacrificed for speed. The tempo of the research being dictated by the demands of the real-world project meant there was not time in the programme to explore questions that emerged. For example the durability of the novel material was not thoroughly investigated, as the detailed design of the shell roof was deliberately developed to limit the exposure of the concrete.
- The need to converge on a single project-solution inevitably ruled out other alternative concretes. This approach resulted in identification of three satisficing (and thus probably sub-optimal) solutions as opposed to gaining a broader knowledge of the solution space in which a range of optimal solutions for different projects might lie.
- As a consequence of the two points above, uncertainty remained in the technology development process.

A knowledge-driven research approach would have followed a different methodology and have produced different results. For example, a knowledge-driven approach is likely to have tested a broader range of lime-SF mortars in order to identify the percentage dosage of SF that resulted in the highest compressive strength. Instead this design-led approach, accepted that the ‘optimum’ content lay somewhere above the maximum permitted by the industry standard and was satisfied to proceed with the design process on the basis of this legislative constraint.

Both knowledge- and design- driven approaches are deemed to be equally valid in the context of academic research, the former being suited to achieving internal consistency and the latter to external correspondence (Katsikopoulos, 2009). Moreover the author would argue that these two alternative research approaches are highly complementary and could beneficially be employed in conjunction with one another in a pluralist approach

23.6 Key limitations of the research approach

It is clear that the breath of this research project has been at the expense of depth, with neither the analytical chemistry nor the management implications, developed as far as a post-graduate study on lime-pozzolan concretes or on design-management processes in construction might have facilitated. Furthermore, had these two tranches of the project been undertaken separately, they would very likely have been conducted by a material scientist and social scientist respectively, individuals whose experience could have shed more light on these wide-ranging, if not unrelated, subjects. As it stands one engineer has been taken on a very far-reaching intellectual journey.

In the case of the lime-pozzolan concrete it is argued that the design-driven approach necessitated and resulted in converge on a single project-solution, inevitably ruling out alternative concrete formulations. This approach, coupled with the lack of chemical analysis (that is also attributed to constraints imposed by the industry programme), is thought to have trapped a high level of theoretical uncertainty in the laboratory research process.

23.7 Key contributions of this research

Not only has this boundary-spanning research project created new knowledge, and with it new technological possibilities, but it has also been seen to be effective in stimulating interest in the construction community that could exploit the knowledge and turn the technological possibilities into future realities. On the strength of the findings of the case study project the efficacy of interest in this novel technology should not to be undermined.

Academic research is not an isolated endeavour; rather it is more or less effective in bringing about change in the broader socio-technical landscape. It is hoped that the research reported in this thesis will inform, or inspire, a number of projects, both in academia and in industry, for the interoperability of social and technical systems is both the source of complexity and the source of creativity.

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APPENDICES

List of Appendices

Appendix A: De Bono selective coding cue card

Appendix B: Cross laminated timber design guide

Appendix C: Rammed earth design guide

Appendix D: School rammed earth test results

Appendix E: Rammed earth storyboard

Appendix F: Lime-pozzolan concrete storyboard

Coding cue card:

White

- Facts and figures
- Believed facts (I think I am right in saying…or similar qualification).
- Checked facts
- ~~Opinions, hunches intuition, judgements, feelings, impressions of the speaker~~
- Reported opinions of others

Red

- Feelings, emotions, intuition
- No explanation or justification required or permitted
- Intellectual feelings 'That idea is very interesting'
- Subjective insight/understanding
- Values

Black

- Difficulties, problems, dangers, obstacles, downsides, weaknesses, risks
- What is wrong, what does not fit, what will not work.
- Logical basis for the criticism – must make sense.
- Caution or risk assessment
- Deficiencies in the thinking process itself e.g. Those figures are not the ones you showed us last time.

Yellow

- Speculative-positive, proffered optimism
- Focus on benefits and values
- Proposals and suggestions
- Desired future on a scale from logical-practical to over-optimistic (likelihood)
- Opportunity identification and making things happen

Green

- Ideas, options, possibilities, routes and alternatives
- Creativity
- Provocation, exploration and risk taking
- Humour and lateral thinking
- Using ideas to move forward e.g. it leads me to think

NOTE: *The production of this series of design guides, on sustainable forms of construction, is a work in progress. Please if you have any comments on this document, can recommend improvements or suggest titles for subsequent guides, then do not hesitate to contact the author, Ellen Grist, who will be most grateful for any feedback.*

Cross Laminated Timber

FOR FURTHER INFORMATION

1. LEWIS, H., 2010. Open Academy Norwich NR7: Project Write Up, Jan 2010. Ramboll UK
2. TRADA CLT Publications: *(available from the TRADA website for members only)*
   WIS 2/3-61: An introduction for specifiers
   WIS 2/3-62: Structural principals
   GD10: Design for project feasibility
   Worked example: 12-storey building
3. STONE, D., 2008. St. John Fisher RC School, Peterborough: Project Write Up. Ramboll UK.

See also:

- http://www.clt.info/index.php?id=5&L=2
- http://www.klhuk.com/site/
- http://www.eurban.co.uk/
- http://www.donaldsonandmcconnell.co.uk/timber-frame-systems.html
- http://www.bkts.co.uk/technical-clt.html

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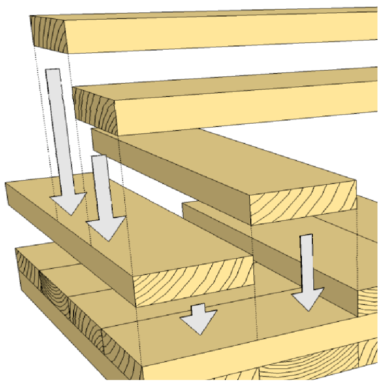

For more information in Ramboll contact:

gavin.white@ramboll.co.uk
or
ellen.grist@ramboll.co.uk

Norwich Open Academy

'Cross laminated timber, as opposed to traditional steel or concrete, can be both a sustainable and a financially viable proposal'[1]

COST

Typically around £900 per m^2 of timber (dependent on the layout and thickness of the panels).

Panel lengths greater than 13.5m are available (up to 20m), but incur significantly increased transport costs.

CLT manufacturers will charge for the whole rectangular area of a panel, including any cutouts or off-cuts.

Scaffolding is not required, as long as edge protection is suitably integrated when erecting the frame.

As all the manufacturers are located in Europe, the price of CLT in the UK is dependent on the exchange rate.

RAMBOLL

Specifying cross laminated timber

KEY DESIGN CONSIDERATIONS

- Cross Laminated Timber (CLT) refers to **load bearing**, solid-timber panels, which can be used for floor, roof and wall panels. The **monolithic panels** are fabricated from alternating layers of softwood planks, typically kiln dried spruce, which are glued at right angles to each other under high pressure.
- The structural panels are extremely versatile and are **precision cut** to the exact shape and size required, before delivery. At an early date designers should confirm the basic panel module with the manufacturer as maximum dimensions do vary.
- Delivery and erection of the pre-fabricated panels, using a crane and lightweight power tools, substantially **reduces programme times** in comparison to traditional wet-trades. Factory cutting of door, window and service holes, to ±1-2mm, allows doors and windows to be pre-ordered, further benefiting programme times. It does however demand early coordination.
- A CLT building is almost **weathertight** on erection of the solid timber frame. The panels can then be used to support cladding internally or externally, or the timber, which is available in a range of grades of surface finish, can be left exposed internally given appropriate fire engineering & spread of flame treatment on the structure.
- A solid CLT floor panel can span up to approx. 7.5m, creating open spaces with **flat soffits**. This gives maximum **flexibility** for locating internal partitions and routing services, which can be directly fixed to the timber.
- The panels are **lightweight**, in comparison to steel/concrete, reducing the requirements for the substructure, resulting in cost and carbon savings. The uniformly distributed line load can typically bear onto simple mass concrete footings.
- Stability is provided by **shear connections** between panels, typically screwed through a stepped rebate, and by diaphragm action provided by the stiff roof and floor panels.

'The academy has raised the profile of CLT in the UK'

Harri Lewis, Ramboll Structures, Cambridge (2010)

ENVIRONMENTAL BENEFITS

- The carbon footprint of the Open Academy was approximately half that of a steel/concrete framed solution. If sequested carbon is included in the analysis, the frame will be carbon negative.
- Timber is a renewable material but it is important to specify FSC or PEFC certified timber to ensure that it originates from sustainably managed forests.
- The manufacture of CLT is an example of zero waste processing, as the offcuts and sawdust can be used as fuel for the factory heating system.
- CLT is supplied in the UK but currently has to be transported from Europe.

CASE STUDY[1]

On completion in 2010, the Ramboll Engineered Open Academy, a £20m new build secondary school in Norwich, became the largest solid timber panel building in the UK, with a floor area of over 9,500m^2.

With a reputation for successfully delivering large CLT projects, this project was an innovation for Ramboll, who took full design responsibility for the timber engineering and detailing, including the connection design. The timber sub-contractor was KLH UK.

A curved facade was formed using faceted CLT wall panels, typically supporting 230mm thick CLT floor panels, spanning up to 7.55m with no intermediate supports. The doubly curved feature roof over the central atrium comprised CLT roof panels, with circular sky lights, supported on 12 glulam arches.

Erection of the CLT frame lasted just 18 weeks, resulting in estimated programme savings of 14-18 weeks. This process required no scaffolding and created virtually no waste.

The negative embodied carbon, associated with the 3,500m^3 of timber in frame, is thought will offset the building's operational carbon for a period of ten years.

MATERIAL PROPERTIES[2]

Thermal conductivity: λ_{CLT} = 0.13W/mK

Density: $\rho_{CLT} \approx$ 500kg/m^3

Charring rate ≈ 0.7mm/min (LenoTech panel)

Sound reduction: < 75dB (LenoTech panel)

Properties should be confirmed by testing.

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Rammed Earth

FOR FURTHER INFORMATION

1. WALKER P. et al., 2005. *RAMMED EARTH: Design and construction guidelines*. BRE Press.
2. HAMMOND G. & JONES C., 2008. INVENTORY OF CARBON AND ENERGY (ICE). Version 1.6a. University of Bath.
3. THOMAS C., 2008. THE GENESIS PROJECT: DEMONSTRATING SUSTAINABLE CONSTRUCTION. The Structural Engineer, 6th May.
4. JAQUIN P., 2009. The strength of unstabilised rammed earth materials. Geotechnique, 59 (5).
5. www.historicrammedearth.co.uk/sustainable.htm

For more information in Ramboll contact:

paul.jaquin@ramboll.co.uk,
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'a high quality and sustainable building technology for walls in housing and other low and medium rise buildings.'[2]

'The high thermal mass of rammed earth walls mean they act to naturally regulate the internal temperature of a building. Earth also naturally regulates the internal relative humidity of the building, producing an improved air quality'.

COST

In previous projects the cost of rammed earth has varied significantly between £190-800/m². It is very dependent on the source of the earth and the cost of the formwork. Hire of the formwork for the lecture theatre at CAT cost £2000/week and it was estimated that the cost of the formwork was approximately half the total for construction of the rammed earth drum structure.

RAMBØLL

Specifying Rammed Earth

KEY DESIGN CONSIDERATIONS

- Rammed earth has been demonstrated to be appropriate for both load-bearing/non-load bearing and internal/external walls. Where additional strength is required the natural soil can be **stabilised** by the addition of lime or cement. Stabilised earth can achieve a dry unconfined-compressive strength of around 10N/mm^2.
- The suitability of the soil on site will have to be determined by **laboratory testing**; 50kg of **sub-soil** should be taken from a depth of at least 1.5m during the site investigation for testing. If the soil is not appropriate it is possible to blend the site soil with a suitable material imported from the local area.
- Moist sub-soil is typically **mechanically compacted** in 100-150mm thk layers in **temporary formwork**. Standard concrete formwork can be used or bespoke formwork can be made to form walls curved in plan.
- Rammed earth walls should be protected from water degradation by building them on a **masonry plinth** and having an **overhanging eaves** detail. In highly trafficked areas some form of protection should be considered against abrasion and mechanical damage.
- The thermal conductivity of earth is relatively high and a 300-500mm thk external wall itself will **not** have a sufficient U-value to meet building regulations. If used for an external wall it should be externally insulated.
- It is important to **construct rammed earth under cover** in the UK, and allowances must be made to construct a temporary roof or to build the rammed earth within the existing building envelope.
- A typical specification for Rammed Earth works is set out in Appendix B of ***Rammed Earth: Design and construction guidelines***[1] by P. Walker et al.

'the building offers a template to the industry on how sustainable materials can be used within new buildings.'

Ian Moore, Project Director of the Genesis Centre, 2007

ENVIRONMENTAL BENEFITS[2]

Embodied energy: 0.45MJ/kg *[for a 300mm thick wall = 270MJ/m^2]*

Embodied carbon: 0.023kgCO_2/kg *[for a 300mm thick wall = 13.8kg CO_2/m^2]*

- In using soil taken directly from the site there is no transport requirement, which directly reduces CO_2 emissions and takes vehicles off the road.
- Passive thermal and humidity regulation provided by the earth means that the HVAC energy requirements of the building can be significantly reduced.
- Rammed earth is inherently recyclable but only if it is not stabilised.

CASE STUDY

The Genesis Centre, at the Somerset College of Art and Technology in Taunton, is a Ramboll example of the use of rammed earth in modern construction. The 400mm thick, 11m long, 2.5m high, rammed earth wall formed one side of the earth pavilion. Being only single storey, with only low loads, it was possible to use natural soil as opposed to stabilised soil.

The original intention was to use earth from the site; however laboratory testing, carried at the University of Bath, showed that the material from the site would have to be blended to attain the required particle grading. This factor, in conjunction with concerns about the volume of soil that would be needed to be taken from a confined site, led to the decision to use soil supplied by the specialist rammed earth subcontractor, Pioneer Cabins, instead.

Whilst material tests were being undertaken and suitable earth sourced, the structure was designed using conservative material properties.

MATERIAL PROPERTIES[1]

Characteristic dry density: *2000kg/m^3*
Minimum compressive strength*: 1N/mm^2*
(or for load bearing walls 2N/mm^2)
Flexural strength: *assume to be 0*
Shear strength: *assume to be 0*
Elastic modulus: *100-500N/m^2*

Properties should be confirmed by testing.

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Properties should be confirmed by testing.

ANALYSIS OF MATERIAL PROPERTIES IN THE LABORATORY

Introduction

The section of the report details the results of testing that was undertaken to investigate the suitability of the site material for construction of a rammed earth wall.

The experimental testing reported herein was undertaken in the soils laboratory in the Department of Civil and Architectural Engineering, at the University of Bath.

All testing was conducted in accordance with relevant standards. Testing methodologies are outlined in this section of the specification along with the results.

The laboratory research has been conducted by Ellen Grist, a Research Engineer in Ramboll, with the support of her academic supervisors: Dr Kevin Paine and Dr Andrew Heath and the laboratory staff. This research has been funded by the EPSRC and Ramboll as part of a collaborative EngD research programme.

Sampling

Earth was sampled from the school playing field (TP2 and TP3) during the site investigation in April 2011. A typical 200-300mm thick band of subsoil was encountered below the topsoil, at depth of approximately 0.2m. The material sampled from the two trial pits was the same by inspection and was deemed to be representative of the subsoil occurring naturally on the site. The material sampled for testing was screened to a maximum particle size of 50mm on site, before being bagged up and taken to the University soils laboratory for testing.

Classification of the soil

The Atterberg limits and linear shrinkage were determined in accordance with BS 1377:2. The results of these tests are summarised in Table 1.

This series of tests classifies the characteristics of the fine material, particles sizes <425µm. The recommended rammed earth properties are from Walker et al. (2005).

	In situ soil	**Recommended for Rammed Earth**
Liquid limit	34.8%	
Plastic limit	24.1%	
Plasticity Index	10.7%	2-30%
Linear shrinkage	16%	<5%
Fine material characterisation		Low-plasticity clay

Table 1: Atterberg Limits

These results demonstrate that the fine material is a low plasticity clay and that it is within the limits recommended for rammed earth. This can be seen graphically in Figure 1.

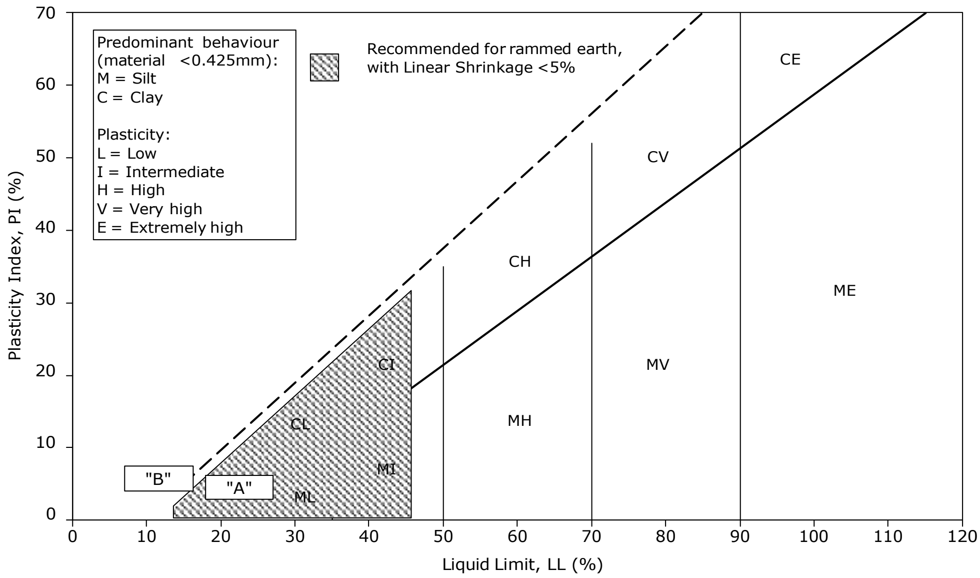


Figure 1: Plasticity chart for school site material

The linear shrinkage of the in-situ site material was higher than the recommended limits for rammed earth. As the high linear shrinkage test result suggested, initial cylinders prepared with the natural material did shown excessive shrinkage with a high degree of surface cracking, when cured in ambient conditions. However this problem was seen to be overcome by blending the insitu material with 15% coarse sand. See the following section on the particle size distribution.

Particle size distribution

The particle size distribution of the insitu sub-soil was determined in accordance with BS 1377:2. The coarse material was graded using wet sieving and the finer material analysed using a hydrometer. The particle size distribution for the sampled insitu material is shown in Figure 2 along with recommended limits for rammed earth (Walker et al., 2005).

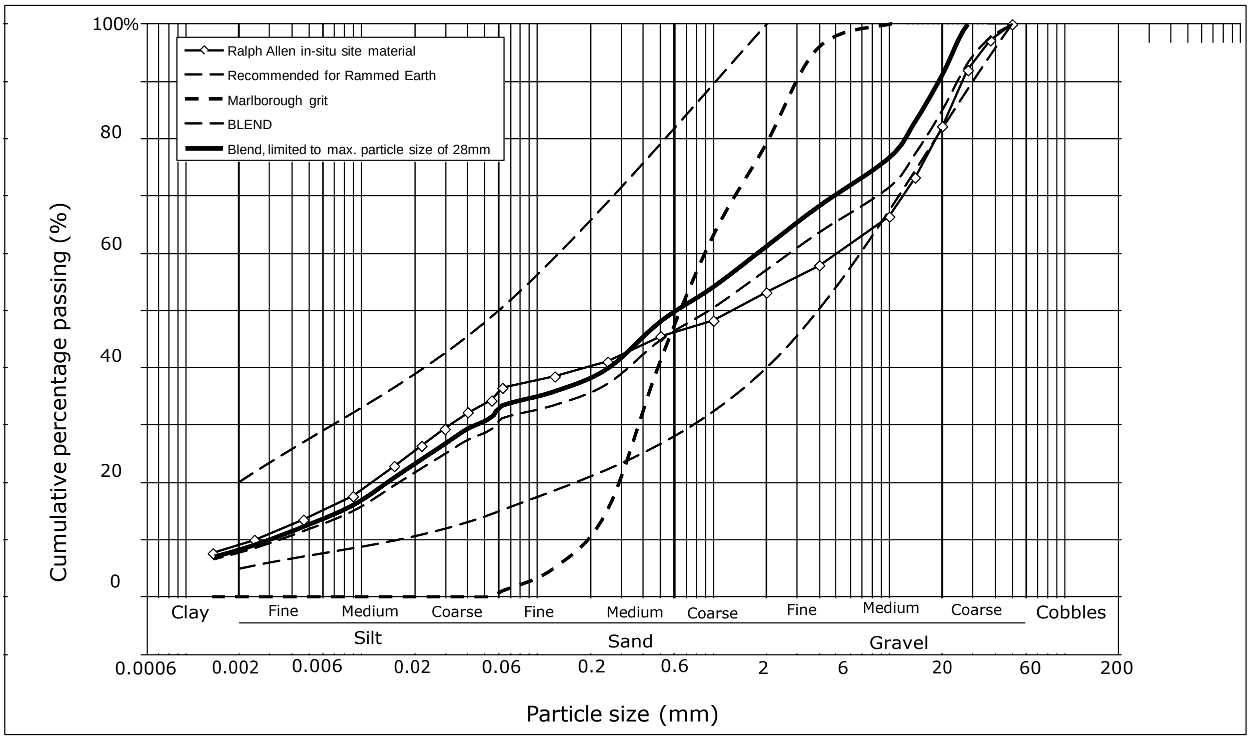


Figure 2: Particle size distribution

The insitu-subsoil was naturally well graded and once large cobbles were screened out, had a suitable particle size distribution for use as rammed earth. For use in the rammed earth wall the material should be screened to a maximum particle size of 28mm, to bring the natural grading within the recommended limits.

Due to the high degree of linear shrinkage demonstrated by testing of the fine material, it is necessary to blend the site material with 15% course sand. The material used and tested in the lab was Marlborough Grit, a Cerney Grit sourced from Stone Supplies. The grading of the blended material is also plotted in

Figure 2, showing a well graded blend falling well within the recommended limits for rammed earth construction.

.

ENGINEERING PROPERTIES

Stabilisation

Although the natural material was unlikely to need stabilisation to attain the recommended compressive strength for a non-load bearing wall, it was recognised in a school environment that stabilisation with a minimal % of cement would be beneficial in improving the abrasion resistance. With reference to the work of Holmes and Wingate (1997) cement, as opposed to lime, was recognised to be appropriate for stabilising the site material, with a liquid limit of 35% , a plastic limit of 24% and a plasticity index of 11%, see Figure 3.

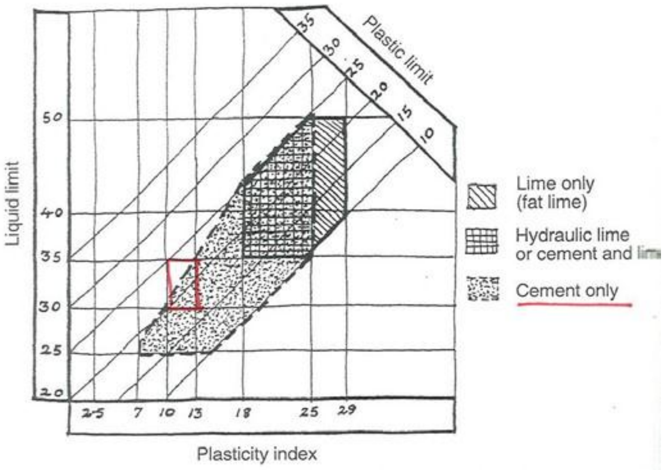


Figure 3: Holmes and Wingate (1997): Interpretation of Atterberg limits for choice of stabilizers

Compaction

To find the optimum moisture content a total of 7 cylinders were compacted at a range of moisture contents and the final dry-density of the resulting samples compared. The test was conducted in accordance with BS1377:4.

The optimum moisture content test was performed on the earth-sand blend with addition of 3% cement. The cement was added to the moist earth-sand blend just before the cylinder was rammed.

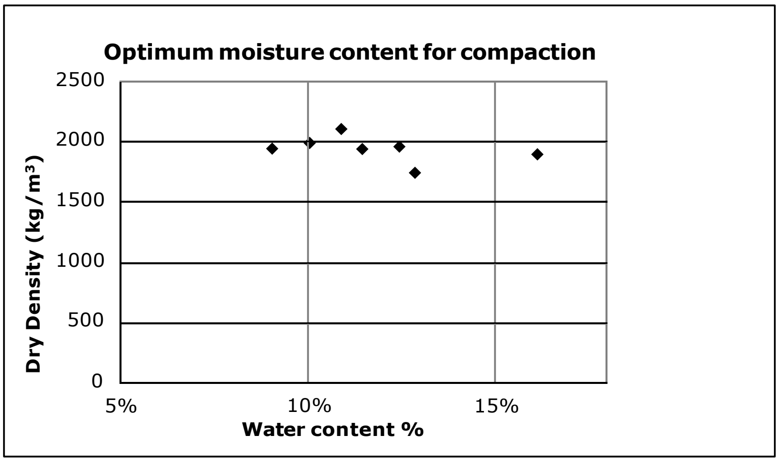


Figure 4: Optimum moisture content for compaction

The test was performed in accordance with BS1377:4, with cylindrical samples compacted in 5 layers, in 1000cm^3 moulds.

This shows the effect of the water content of the sample on the final density. A maximum dry density of 2083 kg/m^3 was achieved at a moisture content of 11%.

Properties of the compacted material

The cylinders that were compacted for testing of the compressive strength were 100mm in diameter and 200mm high. They were compacted manually, in accordance with the standard for heavy-manual compaction, with the material compacted in eight equal layers, with 25 blows per layer.

The earth-sand blend (including 15% Marlborough Grit by mass), was stabilised with 3% general purpose cement and was prepared at a water content of 11%. The lower actual compaction water contents, seen in Table 2, evidences moisture loss due to evaporation during the preparation of the cylinders. This represents the lowest moisture content with small quantities of the material sampled for moisture testing at the very end of the cylinder preparation process.

Sample ref	Compaction water content (%)	Testing water content (%)	Dry-density (kg/m^3)	Compressive strength (N/mm^2)
1	9%	5		2.9
2	10%	4		3.1
3	10%	3		3.2
4	12%	5	1,745	2.7
5	10%	4	1,767	2.9

Table 2: Compacted material properties

The average compressive strength of the samples, f_a is 3.0N/mm^2 with a standard deviation of 0.17.

The cylinders were stored in ambient conditions in the laboratory for 28 days before testing.

The compressive strength of the cylinders was measured after 28 days. The compressive strength was determined by incremental loading of the samples in uni-axial compression until failure, in a Dartec 100kN testing frame.

Figure 5: Compressive strength testing of the school Rammed Earth

The cylinders were capped with dental plaster on the top and bottom faces to ensure a inform loading surface. The constant loading/strain rate applied was 0.5mm/min.

The characteristic strength (F_c) of the blended and stabilised sample, suitable for design purposes, has been calculated according to Equation1.

$F_c = f_a - 1.65(\sigma_n - 1)$ Equation 1

$F_c = 3.0 - (1.65 * 0.17)$

$F_c = 2.7 N/mm^2$

The characteristic compressive strength of the rammed earth sample prepared in the laboratory is 2.7 N/mm^2. This is greater than the minimum $1.0 N/mm^2$ recommended by Walker et al (2005) for a non-load bearing rammed earth wall.

SURFACE FINISH

To date only small-scale cylindrical samples of the rammed earth mix, developed for the school, have been produced in the lab; of these many have been tested to destruction. Given that the rammed earth partition is not load bearing, but rather is an educational statement of the beauty and performance of the naturally occurring site material. It is highly recommended that a small sample wall is constructed, and the finished surface signed off by the architect, prior to starting the wall.

As well as a clearer definition of the individually rammed layers, a greater variation in the natural colour and texture of the finished surface, is both expected and desirable, when the material is rammed at a larger scale.

DEVELOPMENT, CONCLUSION AND RECOMMENDATIONS

Following discussion with the project architect, three final rammed earth cylinders were prepared using 4% white cement. This subtly, but appreciably changed the finished surface appearance of the rammed earth. A slight flecking on the surface, due to the white cement content, looked more natural with creamy-coloured Bath-limestone aggregate. This produced a more desirable surface appearance than the grey cement, which tended to discolour the surface.

For these last two samples the white cement content was increased to 4% to order to further improve the abrasion resistance of the surface.

These three cylinders were also prepared at three different moisture contents around the known optimum for compaction: 11%, 12% and 13%. The sample at 13% water content was evidently too wet and broke in half during extraction from the mould. From inspection during sample preparation, a moisture content of 12% produced the optimal surface finish. The sample prepared at 11%, although found to be optimal for compaction, tending to be slightly more friable on the surface. On the basis of this experimentation, it is recommended that the rammed earth wall is stabilised using 4% white cement and compacted at a moisture content of 12 +/- 1.0 %.

REFERENCES

WALKER ET AL., (2005). Rammed Earth: Design and Construction Guidelines. BRE Bookshop: Watford

HOLMES, S. & WINGATE M., (2002). Building with Lime: A Practical Introduction. Practical Action Publishing: Warwickshire

BS 1377-2:1990. Methods of test for soils for civil engineering purposes. Part 1. General requirements and sample preparation. BSI

BS 1377-2:1990. Methods of test for soils for civil engineering purposes. Part 2. Classification tests. BSI

BS 1377-2:1990. Methods of test for soils for civil engineering purposes. Part 4. Compaction related tests. BSI

01

The Site Investigation (SI) involved digging trial pits around the school.

02

The potentially usable earth was found in a layer approximately 0.5m thick, below the topsoil and above the weathered rock.

03

As the hole was dug it was possible to separate the soil from the layer of sand and stones below.

04

It would be good to find uses for the different sized fractions of the layer of weathered rock. Could some of these produce a suitable limecrete?

05

Stones larger than 50mm across, were easily screened out of the earth sample using a sieve. These would be too big to include in a rammed earth wall.

06

In the lab the soil was 'graded' - it was separated it into different sized particles using a range of sieves of different sizes, stacked one above another.

07

This process is called 'wet sieving' as it is necessary to use water to wash the fine material through the sieves.

08

Once the stones were sorted into different sizes they were dried out in an oven, to remove the excess water, and then weighed.

09

Smaller material, less than 10mm across, was similarly sorted by washing through a series of increasingly fine sieves down to 75µm.

10

A sample of the fine silt and clay particles, passing through the finest sieve, was then graded using a 'hydrometer', which measures rate of sedimentation.

11

A 400g sample of material, which passed through a 425µm sieve, was dried and ground to look at the behavior of the fine material.

12

This material was rehydrated using distilled water to produce a ball of clay, much like that you would use for modeling.

13

The Plastic Limit (PL) of the material is defined as the moisture content at which a 3mm sausage of the clay breaks when you roll it on a glass plate.

14

The moisture content at the Plastic Limit is measured by weighing the broken sausages, before and after drying them out in an oven.

15

More water is added to the clay to determine it's Liquid Limit (LL). At this point the material is soft enough that a specific steel cone dropped onto a sample will penetrate 20mm.

16

Next...calculate the Plasticity Index (PI). This single index tells you alot about the behavior of the clays in the soil and indicates how the soil might be appropriately used.

17

Also...plot a curve showing the grading or particle size distribution of the sample and check that it falls within the appropriate limits for rammed earth.

18

Assess the drying shrinkage of the material and determine the optimum moisture content for best compaction.

19

Ram some cylinders and measure their strength as they dry out. Also what is the abrasion resistance of this dried material?

20

Determine if it is necessary to stabilise the material and if so whether cement or lime would be most suitable.

RAMBOLL

Bespoke lime-concrete: development storyboard

Excavation of the weathered oolitic limestone, from the school site.

The excavated stone was screened through a 50mm mesh into a large hippo bag.

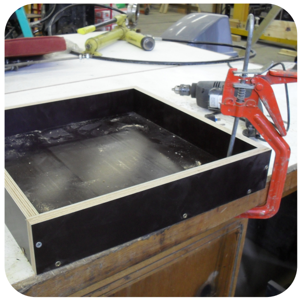
At the lab, large fragments of the weathered rock were removed by passing all the material through a 28mm sieve

Small particles were removed by passing the remaining material through a 6.3mm sieve

The desired large aggregate, containing particles between 6.3 - 28mm.

The hippo bag of site material (2/3 full), was reduced to 2 flat pans of aggregate, around 120kg in total.

Almost 3 bin fulls of material, either side of the required range, were produced and set aside.



400x400x60mm moulds, made of phenolic plywood, were made for casting test panels - for subsequent polishing.

4no. small trial mixes were used to finalise the details of the mix.

Too little superplasticiser and mixing water and the mix won't flow into moulds....

...a fraction too much and the mix turns into a soup.

Between these two extremes in a mix that flows into the moulds, with the aggregate evenly distributed throughout.

story continues over page...

RAMBØLL

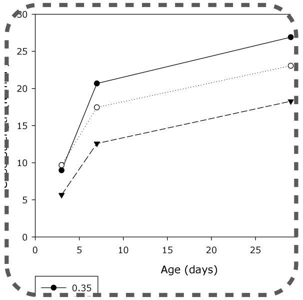
Mix constituents weighed out for a 50kg batch. This will make one 400mm^2 slab and 12no. 100mm^3 cubes.

The site aggregate was blended with a local coarse sand.

Consistency of a mix with a low water to binder ratio (0.35).

The fresh mix was cast into a 400mm^2 slab for polishing trials (by others).

Limecrete cubes were de-moulded having been left under polythene overnight.



Test compressive strength of cubes at 3, 7 and 28 days.

Samples polished with diamond to expose the site aggregate.

Photograph limecrete samples.

Back ground technical specification written to accompany architect's NBS spec.

Production of tender documents.

‘Nothing seems to be more prominent about human life than its wanting to understand all and put everything together’.

Buckminster Fuller